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MICROSCOPIC CHARACTERS OF VEIN CARBONATES.

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ABSTRACT.

The features of vein carbonates in thin sections are described and illustrated. Fillings, replacements, paragenetic relations and metamorphism are noted. The relations of carbonates to ore minerals are mentioned in brief summaries and some interpretations of features in terms of origin are suggested.

PART I.

INTRODUCTION.

THE carbonate minerals are, next to quartz, the most common gangue minerals in veins. They do not show the uniformity that quartz does in composition

and properties, but form a complex double series, and include a few scattered members besides. It is not easy to restrict any discussion of their microscopic features to one species or variety, because of the isomorphous mixtures and zonal growths that involve several members of the group. Probably the most important carbonate gangue minerals in veins are calcite, dolomite, ankerite, siderite, manganosiderite, and rhodochrosite. Other vein carbonates may be important locally, but need less space in a general description. A few are good ores. With this variety of composition it is probably not surprising to find a great variety in their characters in thin sections.

The clearly sedimentary [1] and clearly metamorphic rocks [2] bearing carbonates are not the subject of this paper, but it is noteworthy that such rocks very commonly have carbonate veins in them. Carbonated shear zones in ancient rocks are in a sense replacement veins, included here: and some are rather extensive and not all are easily distinguishable from impure limestones. Limestones are also related to the subject in hand because they are favorable hosts for ore veins—in such rocks the ore veins nearly all have carbonate gangue.

The mineralogic characters of the carbonate group are well covered by earlier papers.[3, 4, 5] A valuable study of the compositions of carbonates in relation to occurrence and thermal zoning was reported by Charlewood [6] with the recommendation that many more such studies should be made. Only a little work is here added to that phase of the problem but qualitative tests have been made on some of the specimens that have interesting features under the microscope.

Lindgren [7] in his masterly report on metasomatism notes and gives sketches of many of the microscopic characters of carbonates, but except in that paper (which covers many other minerals also) the characters of carbonates are described and illustrated only in scattered papers on local deposits. The attempt is here made to compile the references to good examples and illustrations, and add some new examples.

Many geologists, even those well trained in microscopic petrography of rocks, find the characters of veins strange and puzzling. The characters of vein quartz were well described by Adams [8] and the writer has found that paper so valuable in teaching that he hoped to make this work on carbonates a "study for students." A beginning was made by Lloyd Lewis as a senior thesis at the University of Minnesota. The collections in Applied Petrography at Minnesota include several hundred thin sections of carbonates, and

[1] Voigt, Virginia, The textures of limestones. Thesis, University of Minn., unpublished, 1939.

[2] Howell, J. V., Notes on the Pre-Permian Paleozoics of the Wichita Mountain area. Bull. A.A.P.G. 6: 413–425, 1922.

[3] Ford, W. E., Studies in the calcite group. Trans. Conn. Acad. Arts, and Sci. 22: 211–248, 1917.

[4] Winchell, A. N., Elements of Optical Mineralogy. Part II, 69–89, 1933.

[5] Larsen, E. S., and Berman, H., The microscopical determination of the non-opaque minerals. U. S. Geol. Survey Bull. 848, 1934.

[6] Charlewood, G. B., The nature and occurrence of carbonates in veins. Econ. Geol. 30: 502–517, 1935.

[7] Lindgren, W., Metasomatic processes in fissure veins. Trans. A.I.M.E. 30: 578–692, 1900.

[8] Adams, S. F., A microscopical study of vein quartz. Econ. Geol. 15: 623–664, 1920.

many more were made for this particular study. There are representative vein carbonates from all five continents.

In anticipation of the later results it may be said that vein carbonates are almost as ubiquitous (Lindgren says "persistent") as quartz. They range in occurrence from aplites and pegmatites through all thermal zones of hydrothermal deposits to cold water veins. Many of the features seen may suggest the probable origin and occurrence of the carbonates, but there are many uncertainties and the interpretations may be a subject of discussion for some years. A few of the more satisfactory interpretations are noted with the descriptions here given, but many features are described without explanation. (Two discussions of interpretations are to be separately published.)

THE GENERAL FEATURES OF CARBONATES OF VEINS.

The features of carbonate veins resemble the features of veins in general as described and illustrated in most textbooks of ore deposits.[9-12] Many fill openings, many others replace the walls of fractures and still others result from the oxidation of sulphide ores.[13] They range in length from a fraction of the length of a thin section to great masses a mile long. Some have completely filled the open spaces, and others leave vugs or drusy cavities. Many veins contain fragments of the wall rocks—"horses," if they are large enough to disturb the mining. As the abundance of fragments increases, veins grade into breccias, and there has been much discussion of the "unsupported structures."[11, 14-16] The relation of carbonates to each other and the other vein minerals, taking account of their origin and sequence, is included in the subject of paragenesis.

It is commonly believed from field experience that highly siliceous magmas give off more siliceous emanations than basic magmas; from the basic magmas more carbonate may be expected. Spurr[17] says solutions from basic magmas are calcic with little silica.

COMPOSITION AND TESTS OF VEIN CARBONATES.

Chemical Tests.—Since the carbonates are not easily and definitely distinguishable in thin sections, a great many are tested by chemical methods. Tests may be qualitative or quantitative.

Probably a hundred samples are tested for effervescence in cold dilute HCl, for one that is more thoroughly treated. Such acid reacts vigorously with *calcite* and a drop of acid is almost neutralized in a few seconds; but the acid

[9] Rickard, T. A., Vein-walls. Trans. A.I.M.E. 26: 193–241, 1896.
[10] Halse, Edw., Structure of ore-bearing veins of Mexico. Trans. A.I.M.E. 32: 285–302, 1902.
[11] Spurr, J. E., The Ore-magmas, 1923.
[12] Berg, G. E. W., Mikroskopische Untersuchungen der Erzlagerstätten, Berlin, 1915.
[13] Loughlin, G. F., The oxidized zinc ores of the Tintic district, Utah. Econ. Geol. 9: 1–19, 1914.
[14] Talmage, S. B., The significance of "unsupported" inclusions. Econ. Geol. 24: 601–610, 1929.
[15] Farmin, R., Dislocated inclusions in gold-quartz veins . . . California. Econ. Geol. 33: 579–599, 1938.
[16] Berg, Von G., Der Füllung der Gangspalten. Zeit. Prakt. Geologie, 46: 219–225, 1938.
[17] Op. cit., p. 625.

reacts more slowly with *dolomite*, and a drop continues to effervesce for 30 to 60 seconds. If these two minerals covered the whole range of vein carbonates the test might be satisfactory, but there are so many others and they have such a wide range of activity that more detailed tests are needed. They are described in chemical texts and reference works,[18, 19] and need not be elaborated here. Tests may be needed for Ca, Mg, Fe, Mn, and a number of other elements. Even qualitative tests may give a fair estimate of the relative abundance of these four elements.

One precaution may well be noted when all four of the common metals of carbonates are to be sought. Carbonates are commonly impure with more or less hydrous oxides of iron and manganese. If an attempt is made to dissolve the carbonate in weak acid without dissolving the oxides, it may lead to errors. The hydrous oxides (and even the red oxides of iron) are so soluble in cold dilute HCl that the test may lead the petrographer to think the metal was dissolved from the carbonate. It is difficult to be certain whether iron is isomorphously mixed with calcium in a carbonate when the crystals are coated with fine dusty iron oxides.

Stains.—Related to chemical tests are the staining methods. Some of the carbonates may be stained a characteristic color by certain treatments and reagents whereas others are not, or are differently affected. Most of these, like the test of effervescence, distinguish one carbonate from another, but largely ignore the rest of the rather long series. Nevertheless, several have proved useful.[20–27]

In spite of the rather widely recommended staining methods, caution is necessary because men disagree, not only on the behavior of a mineral from different sources but even on specimens from a single district. The "personal equation" is probably important in staining carbonates.[28]

Microscopic Tests.—The microscopic characters that are the subject of this paper are observed mostly in thin section and, after long practice, the kind of carbonate in some thin sections may be estimated fairly well even without chemical tests. Several of the helpful features may be overlooked by the beginner if attention is not called to them. Suggestions of composition may be gained from the (*a*) indices of refraction, (*b*) twinning, (*c*) color, (*d*)

[18] Hillebrand, W. F., and Lundell, G. E. F., Applied Inorganic Analysis, 1929.

[19] Kolthoff, I. M., and Sandell, E. B., Textbook of Quantitative Inorganic Analysis, 1943.

[20] Twenhofel, W. H., and Tyler, S. A., Methods of Study of Sediments, 1941.

[21] Faust, G. T., The differentiation of magnesite from dolomite. ECON. GEOL. 39: 142–151, 1944.

[22] Gaubert, P., The . . . rhombohedral carbonates. Bull. Geol. Soc. France Min. 42: 88–120, 1919.

[23] Keller, W. D., and Moore, G. E., Staining drill cuttings for calcite-dolomite differentiation. Bull. A.A.P.G. 21: 949, 1937.

[24] Berg, G. E. W., Mikroskopische Untersuchungen der Erzlagerstatten, Berlin, 1915, pp. 61–63.

[25] Ross, C. S., Origin of the copper deposits of the Ducktown type in the southern Appalachian region. U. S. Geol. Survey, Prof. Paper 179: 1935.

[26] Kirchberg, H., The determination of ankerite in siderite ores, Ber. und hüttenmänn. Monatsh. Montan. Hochschule Leoben 88: 74–77, 1940.

[27] Douglas, G. V., King, A. M., and Misick, J. D., Staining tests for dolomite. ECON. GEOL. 39: 69–70, 1944.

[28] Smith, W. T., Calcite-dolomite staining tests. ECON. GEOL. 38: 420–422, 1943.

shapes, (*e*) texture and structure, (*f*) occurrence, and (*g*) association and oxidation products. Each of these deserves a little explanation.

(*a*) If the carbonate is mounted in balsam its indices of refraction range so widely that its relief in one position may be very different from that in a different position. English petrographers say that calcite "twinkles" as the stage is rotated, and the term is an apt one. There is a general relation also between high index and shagreen—the apparent roughness of surface. This is especially prominent in carbonates, because the softness and good cleavage of the crystals tend to leave the ground surface covered with fragments (or twinned portions) in different orientation from the main crystal. These characteristics result in a conspicuous *dustiness,* and if the index is high the very dusty grains seem almost opaque. Lindgren noted that siderite, with the highest index of the common carbonates, had been mistaken for leucoxene, because in fine grained aggregates it is opaque.

TABLE I.

CARBONATE INDICES AND SPECIFIC GRAVITIES.
(Mostly from Larsen and Berman.)

Calcite Group.

	ϵ	ω	Sp. G.
Calcite, $CaO \cdot CO_2$	1.486	1.658	2.715
Dolomite, $CaO \cdot MgO \cdot 2CO_2$	1.500	1.681	2.87
Magnesite, $MgO \cdot CO_2$	1.509	1.700	2.96
(Intermediate are breunnerite, mesitite, pistomesite, and sideroplesite)			
Siderite, $FeO \cdot CO_2$	1.633	1.875	2.89
(Intermediate are oligonite, and manganosiderite)			
Rhodochrosite, $MnO \cdot CO_2$	1.597	1.817	3.70
Ankerite, $CaO\ (Mg, Fe)O \cdot 2CO_2$	1.518 to 1.547	1.698 to 1.749	2.95 to 3.2
Smithsonite, $ZnO \cdot CO_2$	1.621	1.849	4.398
Spherocobaltite, $CoO \cdot CO_2$	1.600	1.855	4.1

Aragonite Group.

	α	β	γ	Sp. G.
Strontianite, SrO, CO_2	1.520	1.667	1.667	3.7
(Intermediate bromlite)				
Witherite, $BaO \cdot CO_2$	1.529	1.676	1.677	4.3
Aragonite, $CaO \cdot CO_2$	1.530	1.680	1.685	2.94
(Intermediate tarnonsitzite)				
Cerussite, $PbO \cdot CO_2$	1.804	2.076	2.078	6.5
Malachite, $Cu(OH)_2 \cdot CuCO_3$	1.655	1.874	1.909	4.0
Azurite, $Cu(OH)_2 \cdot 2CuCO_3$	1.730	1.758	1.838	3.8

Dustiness in carbonates deserves a separate paragraph. Aside from the dustiness due to shagreen, to fragmented carbonate, and to twinning structures, there may be a dustiness caused by fineness of grain and by very fine inclusions such as clay. Sometimes fine minerals may be recognizable but commonly in a vein carbonate the very fine clay (and others) are identified

only as dust. In the California mercury ores (Fig. 87) and in the carbonates of the Couer d'Alenes in Idaho, for example, the dusty carbonate looks brown in transmitted light and white by reflected light, greatly resembling the color effect of very fine kaolin in thin sections of weathered feldspar. It would need a test for an insoluble fine residue to determine whether the carbonate itself could be so fine grained as to give this optical color effect. In many of the carbonate ores there are coarser dusty inclusions—our collections exhibit a dozen ore minerals and about as many gangue minerals as very small abundant inclusions. No doubt much of the dust is too fine to identify in microscope slides at ordinary magnifications. Liquid and gas inclusions are seen in some of the vein carbonates.

In a careful study of index of carbonate grains, the estimates of index should be based on the high index (omega) rather than the variable index (epsilon)—the grain may not be in the correct position to show the minimum. The high indices range from 1.658 in calcite to 1.875 in siderite (2.078 in cerussite). This is a wide range so that the relief is helpful in estimating which carbonate is present and whether two carbonates are associated (Figs. 1 and 2).

If material is available for a check of the indices by immersion of powders in oils, the nature of the carbonate can be much more closely estimated. Again, the observations are best made on the maximum index shown by the mineral.

(*b*) It is commonly noted that hand specimens of calcite show twinning striations in a different relation to the cleavage from that shown by other carbonates. The bands in calcite are parallel 0 1 $\bar{1}$ 2, those in dolomite and ankerite are not.[29] In thin sections I have not found this of much value. Twinning bands and cleavages are cut at random in making the section; the bands may be numerous, crossing in two and even three directions; and the boundaries of the twinned plates cause a parting that is so much like cleavages that the determination is seldom satisfactory. When three sets of bands cross a crystal, one set is almost sure to lie in the acute angle and another in the obtuse angle of any cleavages seen.

A more generally useful suggestion is that calcite shows twinning in thin section very much more commonly than dolomite does. The mere presence of the twinning bands is a strong indication of calcite. It should not be depended upon as infallible, for some dolomites (Fig. 12) have as perfect twinning as any calcite. It seems that twinning as a criterion of carbonate composition is more useful in rocks of sedimentary origin, than in veins.

(*c*) The color of carbonates is best seen in hand specimens and involves little that needs discussion. Green malachite, blue azurite, brown siderite and rose pink rhodochrosite are commonly recognized. Siderite and rhodochrosite may at times show a surprising lack of color, especially in thin sections, and both need chemical tests as to possible isomorphous admixtures.

(*d*) The textures and structures of vein carbonates are only vaguely suggestive of composition. For example, certain coarse massive veins with comb structures suggest hypothermal origin, and carbonates of that origin are likely

[29] Rogers, A. F., Polysynthetic twinning in dolomite. Amer. Mineralogist, 14: 245–250, 1929.

to be siderite or ankerite; though the conclusions are not dependable and selected samples may prove to be exceptions. See also the last section of this paper.

(*e*) Occurrence is related to association and texture but should be noted separately as evidence of composition. Veins deposited from cold water are likely to have different carbonates from those deposited as hypothermal veins. A vein carbonate with tourmaline and pyrrhotite in "mutual boundaries" is expected to be siderite or ankerite, but a carbonate intergrown with adularia or fluorite is more likely calcite.

(*f*) The association may help in various ways to identify carbonates. For example, when a dolomite is partly silicated, the magnesium becomes serpentine, or talc, or enstatite, or olivine before the calcium reacts. With such magnesium silicates expect calcite as a matrix. Later veins crossing serpentine, however, may be highly magnesian—even fairly pure magnesite. Again, the carbonates in veinlets crossing iron formations (Figs. 3, 4) are siderite perhaps six or eight times out of ten. Purington [30] says that at Telluride, Colorado, if the associates of carbonates are usable at all, sphalerite is with rhodochrosite and galena with calcite. Manganosiderite is said to be rarely associated with rhodochrosite.[31] Many other associations are helpful.

The oxidation of rhodochrosite produces black oxides, that of siderite more commonly reddish or yellowish brown; but calcite almost always has no component that is oxidizable and hence it usually stays white. Dolomite, ankerite and others carrying a little iron are easily confused with siderite in their weathered condition. It has been shown that dolomite very commonly carries enough iron to weather brown or pink, but some large dolomite formations and probably some vein dolomites are very nearly free from iron. Coatings of the products of weathering may be seen in thin section about as well as in hand specimens (Fig. 5).

Caution should be used in this interpretation because a vein with iron sulphides may be oxidized so that hematite stains the edges of grains of a carbonate that had no iron in it to start with. This is not at all uncommon in calcite gangue. A Mexican vein with brown stained carbonate and fresh pyrite must have had original iron in the carbonate. At Embreeville, Tennessee, cerussite is brown from limonite stain; this is not from iron carbonate, but from pyrite that was being oxidized by the same waters that formed cerussite from galena. Smithsonite in most oxidized zinc ores is similarly stained.

Several of these features may prove helpful in a particular district after a careful study of the carbonates has been made, without in any way implying that the same features would be usable in the same way in another district. The local habits of a series of carbonates may help a great deal. In Eastern Tennessee, for example, the carbonates of the zinc deposits are calcite and dolomite; of these Secrist [32] says calcite is the more transparent, has the better

[30] Purington, C. W., . . . Telluride quadrangle, Colo. U. S. Geol. Survey Ann. Rept. 18, Pt. III: 789, 798, 1898.

[31] Hewett, D. F., and Pardee, J. T., Manganese in western hydrothermal ore deposits. Lindgren volume, A.I.M.E., p. 679, 1933.

[32] Secrist, M. H., Zinc deposits of East Tennessee. Tenn. Div. of Geology, Bull. 31: 30, 1924.

cleavage and better crystal form. At Leadville Emmons [33] reports the siderite that accompanies the sulphides carries considerable manganese.

CRYSTAL FEATURES OF VEIN CARBONATES.

The crystals of the most common carbonates are rhombohedral, and this fact seldom services to distinguish one from another. Most crystal studies of carbonates are based on crystals found in vugs, where the growths of crystals have not mutually interfered with their neighbors, as they have in most thin sections. The forms are numerous. Palache [34] reports 138 forms in one district. Schaller [35] found crystals that look octahedral. Locally the rhombohedrons of siderite, manganosiderite and dolomite are notably curved or saddle shaped.[33, 36, 37] Perhaps one per cent of the calcite grains in thin sections show cross sections suggestion scalenohedrons (Fig. 10). From a fairly wide experience with veins I estimate about one one-hundredth of one per cent show other crystal forms in thin section.

Odd six-sided platy aragonite twins occur, and are reported by Andrews and Schaller [38] to be locally replaced by dolomite.

Etching and corrosion of crystals are rather common in such soluble minerals as carbonates, but thin sections rarely show characteristic forms or surfaces.

Aside from the forms in vugs, already noted, the cleavages are perfect in the rhombohedral carbonates (Figs. 5, 53, 80, 81, etc.); much less so in the orthorhombic forms. Small rhombohedrons in thin section commonly show no cracks, and even large ones may be almost free from visible cracks if the cleavages are inclined to the plane of the section. The cleavage is made more notable in many carbonates by the introduction of colored or opaque minerals, and the replacement of some of the carbonate along the cleavage cracks (Fig. 6).[39, 40] Some magnetite inclusions of rhombic forms seem to follow the dolomite cleavages (Fig. 7) in Cuyuna iron-bearing rocks. The quartz along carbonate cleavages is often left as a network of blades when the carbonate is later leached, but this is rarely preserved in thin sections unless the mesh is filled with later minerals (Figs. 70, 75). A parting related to multiple twinning closely resembles a cleavage.

Zoned structures in crystals of carbonate are very common in thin sections. Dusty cores in dolomite rhombs are perhaps most familiar. Part of the dust may be organic or graphitic material included in the growing crystal. In slates and other metamorphic rocks carbonate rhombs replace the rocks near

[33] Emmons, S. F., et al., The geology and ore deposits of the Leadville Mining district. U. S. Geol. Survey, Prof. Paper 148, 1927.

[34] Palache, Charles, Crystallography of calcite from the Lake Superior copper mines. Am. Mineralogist 29: 35–48, 1944.

[35] Schaller, W. T., Octahedron-like crystals of calcite. Am. Mineralogist 27: 141, 1942.

[36] McKnight, E. T., Lead and zinc deposits of northern Arkansas. U. S. Geol. Survey Bull. 853, 1935.

[37] Dana, J. D., A System of Mineralogy, 6th Edition. Pages 272 and 276, 1911.

[38] Andrews, D. A., and Schaller, W. T., Dolomite pseudomorphs after crystals of aragonite. Amer. Miner. 27: 135–140, 1942.

[39] Johnston, W. D., Jr., Gold quartz veins of Grass Valley, California. U. S. Geol. Survey, Prof. Paper 194, 1940, Plate XII E and p. 52.

[40] Refer to footnote 12, p. 154, Fig. 62, given on a preceding page.

carbonate veins, and carry zoned inclusions of the earlier metamorphic minerals (Fig. 9). Inclusions of liquid with gas bubbles are illustrated by Ross.[25] They are more difficult to see and identify in carbonate than in quartz, because the double refraction obscures the image in random position. Wells and Waters [41] show good zones in siderite. Fearnsides [42] notes zones of abundant spangles of pyrite. Many other minerals, even some ores, form zones of inclusions (Fig. 8) especially in epithermal deposits.[43] Recrystallization seems to have a tendency to eliminate inclusions. Zoning by alternations of different compositions in an isomorphous series is even more common in carbonates than zoning by inclusions. The zones may differ in color and relief (Figs. 10, 14, 15, 16, 17). Many of the zones are curved. Zoned carbonates are shown in the good illustrations of a number of earlier papers.[44, 45] The interpretation of zoning as a criterion that crystals grew in open space is not conclusive, but it is probable that more than half the zoned crystals of veins grew in open spaces.[46]

Secondary growths of fragmental grains such as are common in quartzite, are rare in carbonate veins, but some breccia fragments may be enlarged by growth of the carbonate of the fragment. Phantom veinlets (Figs. 45 and 46) where abundant may be thought of as the secondary growth of the cement of a crackle-breccia.

Twinning according to several laws is recognized in the texts and, as noted above, the multiple twinning appears commonly as bands of interference colors in thin section (Figs. 11, 12, 13, 92, 93, 94). The bands may run in one, two, or three directions in the section, but are of little value in interpretation of vein carbonates.

Carbonate crystals with primary *curved faces* have long been known, and Dana [37] shows sketches of saddle-shaped dolomite and curved siderite. S. F. Emmons, et al.,[47] illustrate curved blades of manganosiderite in vugs at Leadville, Colorado. In tiny vugs the curved flat rhombohedrons look almost platy and grow in a position such that the plates (planes of the *a* axes) are normal to the wall of the vug. They can be seen with binoculars but vugs are rarely preserved in thin sections. Nevertheless curved faces, zones and cleavages are common in thin sections (Figs. 14, 15, 16, 17, 90, 94). The petrographer familiar only with rocks is inclined at first to attribute curved crystals and curved cleavages to deformation because they much resemble the bent feldspars of deformed gneisses. No doubt some marbles and scattered veins contain bent carbonate (Fig. 91), but a much greater part of the curved carbonates grew in that form. An absence of granulation in connection with the curved crystals is enough to raise doubt of deformation. The curved

[41] Wells, F. G., and Waters, A. C., Quicksilver deposits of southwest Oregon. U. S. Geol. Survey, Bull. 850, 1934, Plates 5, 10, 11, 19A.

[42] Fearnsides, W. G., Proc. Geol. Soc. London for 1936–1937, pages V and VI.

[43] Lindgren, W., Mineral Deposits, 3rd Edition, 1928, p. 521.

[44] Irving, J. D., Replacement ore bodies and criteria for their recognition. ECON. GEOL. 6: 527–561 and 619–669, 1911, Plate 14.

[45] Ferguson, H. G., and Gannett, R., Gold quartz veins of the Allegheny district, Calif. U. S. Geol. Survey, Prof. Paper 172, 1932, Plates 33A, B, C; 34C.

[46] Footnote 8, p. 632.

[47] Op. cit., Plate 47D.

crystals in open vugs above mentioned definitely prove that many have not been deformed.

In one sense, the flamboyant structure (Fig. 30) shows curvature, but it is a very special sense. The flamboyant grains have not been deformed but show a pronounced wavy extinction.[48]

In connection with curved carbonate grains there is in some thin sections an odd optical effect much like minute interference figures—right angled black crosses with colored rings (Fig. 18). In calcite rocks somewhat similar figures are formed by radial aggregates in fossils, oolites or veins (Figs. 19, 20) but these differ in several respects. In the first place the curved crystals do not show the figure until thrown out of focus about .2 mm., up for some, down for others; whereas the radial aggregates show a cross when the slide is in focus. When the curved crystal is in focus the extinction is wavy, but the shadow is wide and not associated with the colored rings. Furthermore, a curved crystal can be seen and located where the figure is developed, and such curved crystals can hardly be mistaken for radial aggregates. (Compare Figs. 17, 18 and 19, 20.) The most striking figures in the Minnesota collections are from an old specimen of stibnite ore, recorded in 1901 as from the "Cleopatra Mine." The carbonate is a manganiferous calcite. Another ore with notably curved carbonates and some approach to these figures, is the silver ore with carbonate gangue at Bannack, Montana. In this some of the carbonate is in radial groups, but the best figures are given by curved rhombohedrons without visible radial structure.

A "feathered" structure, such as is common in vein quartz crystals, is less common in carbonates. One thin section from carbonates of the Keeweenawan shows zones of differing dustiness, and the outer zone seems to be feathered about like the outer zones of many quartz crystals; but it is not very perfect (Fig. 21). Ferguson and Gannett[45] refer to "feathery" carbonate but it may be an aggregate of divergent needles rather than an internal crystal structure. Adams[49] classed both flamboyant and feathered structures as "anomalies."

PRIMARY STRUCTURES AND TEXTURES OF VEIN FILLINGS.

The structures and textures of veins need the largest number of illustrations and examples, and, have actually had many scattered illustrations in earlier papers. The crystal features noted in the preceding section and the features of deformation following are almost in the nature of accessory material for this main topic.

A single simple vein with one carbonate is commonly *even-granular* ("mosaic") and massive (Figs. 61, 82). The grain may be as coarse as 1 centimeter (Fig. 81) or as fine as one-tenth millimeter (Fig. 82). Commonly tiny veinlets are finer grained than larger veins. Where the crystals tend to grow large but the joint opening is narrow, the crystals grow long and meet adjoining crystals with contacts that are nearly normal to the plane of the

[48] White, W. H., The mechanism and environment of gold deposition in veins. ECON. GEOL. 38: 512–532, 1943, p. 528, Fig. 10.

[49] Footnote 8, pp. 628–629.

joint—the vein looks "blocky" (Fig. 22). A few of the coarse intergrown carbonate grains may appear "sutured" (Fig. 13) rather than in a mosaic. Poikilitic inclusions of small grains in larger ores are not uncommon (Fig. 13).

Cavities in carbonate veins are so fragile that thin sections seldom show euhedral crystals. *Vugs* and *druses* commonly seem imperfect, and the forms at crystal terminations may be cleavage surfaces as often as results of growth. Where later quartz fills a vug lined with carbonate the combination is commonly saved in thin section (Fig. 23). Any of the common carbonates, however, may line the vugs. A quartz-barite-galena ore from the White Raven mine, Boulder County, Colorado, has dolominte in platy curved crystals in vugs.

Cross fiber veins of carbonate are fairly common and our material includes a large number of veins from eight or ten widely scattered areas. Some show fibers normal to the walls, others diagonal and in erratic deformed positions. Taber believes the walls of such veins were displaced by the growing crystals, without much replacement of the walls. The evidences are so conflicting that several students of veins doubt his theory. After several years of public presentation of his idea Taber [50] presented a concise summary of the "facts" which he feels his theory accounts for, and asks anyone who questions his theory to show that another theory accounts for the facts as well. The present study of carbonates does not settle the argument but raises questions as to a number of the "facts" in Taber's late summary.

He implies that most of the wall rocks of fine fiber veins are fine-grained rocks. Fig. 83 shows fine calcite fibers grown on pebbles and the pebbles of the rock are up to an inch in diameter.

He says the cross fiber veins are always composed of a single mineral which is either a constituent of the wall or may be derived from minerals that are. This, he concludes, indicates that all cross-fiber veins are lateral secretions from the walls. Fig. 24 shows quartz and calcite fibers together. Fig. 83 shows fibrous calcite on pebbles of a variety of different rocks from quartz to basalt, but no recognized limestone.

He says that the walls are sharply defined, and concavities in one wall match opposite convexities. Fig. 42 shows inclined fibers which may indicate the direction of separation of the walls, and this is confirmed by the offset of a tiny earlier veinlet; but if these evidences are correct, the concavities and convexities in the walls do not match—they indicate replacement. The same sort of evidence appears in Fig. 51 and in many calcite veins of our collection.

He says that in a single vein the fibers are parallel. Fig. 83 shows radial growths from curving surfaces.

He says that lengths do not appreciably vary because of irregularities in the strike of the walls. Fig. 51 shows a striking variety in lengths of fibers.

He notes that curves in fibers in veins cannot be explained by replacement or recrystallization *in situ;* but metamorphic deformation seems to explain them, whatever the method of formation.

Thus our abundant material on fibrous carbonate veins gives little support to Taber's facts of occurrence. His arguments have some merit and there

[50] Taber, S., The origin of veins. Eng. and Min. Jour., Nov., 1926.

may be veins that originate as he suggests. In the San Manuel exploration near Tiger, Arizona, calcite veinlets follow cleavages in biotite, and locally swell out into lenses deforming the adjacent biotite cleavages. Some of the calcite is in crude cross-fibers and intergrown with chlorite. At other places carbonates seem clearly to become fibrous (1) by metamorphic deformation, (2) by replacement, and (3) by growth into open space as if an odd comb structure.

Comb structure is not as regular and characteristic in carbonate veins as in quartz veins. Nevertheless, there are many examples of parallel or subparallel growths normal to vein walls (Fig. 25). They may have any of the common compositions. Some of these growths of carbonate minerals show the characteristic *flamboyant* structure (Figs. 26, 30), well known in quartz. Prisms growing from a base into open spaces such as vugs tend competitively to increase in width at the free end, spreading like a gas flame. Those that succeed crowd out a number of their neighbors. There is a sort of transition from parallel prisms in a comb structure to flamboyant crystals, and from those to *radial* groups. In the flamboyant grain it is not as easy to see the contacts of diverging grains as in the radial groups (compare Figs. 29–30 and 27–28).

Radial groups of elongated grains are fairly common in occurrences of each of the principal carbonates (Figs. 27, 28). They may grow around centers that appear accidentally scattered along the walls of veins, or around projecting points and small inclusions in veins (Fig. 34). Carbonate amygdules also commonly show radial structures. The elongated carbonate grains show extinction nearly parallel to their lengths, so that the radial aggregate shows a dark cross that keeps its position as the stage is rotated. This is clearly a different effect from the interference figure derived from curved crystals. A small fine grained radial group approaches the condition of a spherulite and may show concentric layers as well as radial pattern (Fig. 19).

Crustification which is a common megascopic character can be seen in some thin sections. The direction of growth of successive crusts, with different texture or structure, is indicated by crystal terminations projecting into the younger layers (Figs. 31, 34). The crusts may be symmetrical from the opposite walls of the vein (Fig. 33) or may grow almost wholly from one wall. A series of crusts upon a projecting point or around a fragment makes the *cockade* structure (Fig. 34). A curved crust with curved zoned carbonate crystals (Figs. 14, 17, 29) closely resembles the "coxcombs" of marcasite, a "Gothic arch" structure.

A rounded structure in the carbonate at Cobalt, Ontario, is described by Bastin [51] as in *rosettes*, or forms like *tubercles*. His plate II shows the forms, but the interpretation may involve replacement [52] or collodial deposition.[53] Some silver in the carbonate assumes a dendritic or arborescent structure.[54] The hypothermal copper ores of Ducktown type have pyrite in "colloform" [29]

[51] Bastin, E. S., Significant mineral relations in the silver ores of Cobalt, Ontario. ECON. GEOL. 12: 219–236, 1917.

[52] Guild, F. N., A microscopic study of the silver ores and their associated minerals. ECON. GEOL. 12: 297–353, 1917.

[53] Lindgren, W., Gel replacement. Proc. Nat. Acad. Sci. 11: 5–11, 1925.

[54] Ellsworth, H. V., A study of certain minerals from Cobalt, Ontario. Ont. Bur. of Mines 25: I, 200–243, 1916.

structures in calcite,[55] although other sulphides in the same calcite matrix are in more ordinary crystal forms. Watson [56] shows concentric sulphide structures associated with carbonate veins, and calls them colloform though some of them resemble the "tubercles" at Cobalt.

Other concentric structures with radial fine fibers are commonly attributed to colloidal deposition but carbonates probably have less tendency to form colloids than silica has. Some cold water deposits of very fine grain may have originally been collodial. Since they are crystalline as found they may be *metacolloidal* structures; but when carbonates show such structures the possibility of a cockade origin should be considered. Lindgren [57] has interpreted some carbonate layers as colloform, and many of the malachite incrustations seem to be metacolloidal (Figs. 35, 36).

The interpretation of flamboyant, radial and concentric structures is not wholly agreed upon. Colloform structures suggest cold water or possibly epithermal veins. Flamboyant, feathered and cockade structures seem to be more numerous in epithermal than in hypothermal veins, but flamboyant carbonates are not rare in the hypothermal deposits. Adams [58] reported that such structures in quartz had not been observed in veins of moderate or great depth.

Vein Systems and Complexes.—The simplest systems of veins are those filling parallel joint openings (Fig. 37). Where the veins are not wide and the joints are closely spaced the system is referred to as *joint veins,*[59] or a *book structure.*[60] A system of veins cutting diagonally across competent and incompetent layers may change direction in the competent layers (Fig. 38).

A *coordinate system* of veins nearly at right angles to each other and simultaneously filled is not uncommon (Fig. 39). Where *branching veins* are not approximately at right angles (Figs. 40, 47, 82) they should probably not be called coordinate. Ross [61] shows a good example. These can ordinarily be distinguished even in thin sections from two systems of *crossing veins* of different age (Figs. 41, 42) by the different structure or banding in the two.

Where later veins follow along the margin of early veins or along the center, they form a *"reopened" banded vein* (Fig. 43). Many such veins have been illustrated in the texts and articles about veins. Purington [62] shows reopened veins with some carbonate in the vugs. Such banding is commonly combined with a crustification and there have been examples of uncertainty as to the origin of the banding. Even the replacement bands, noted later, may be confused. Johnston [63] gives illustrations from Grass Valley. Ferguson and Gannett [45] show that two generations of carbonate have different textures, in the Allegheny district.

[55] Footnote 25, Plate 43D.
[56] Watson, E. DeP., Colloform sulphide veins of Port au Port peninsula, Newfoundland. Econ. Geol. 38: 621–647, 1943, Figs. 4–17.
[57] Footnote 43, p. 588, Fig. 196.
[58] Footnote 8, p. 630.
[59] Gilbert, G. K., Joint veins. (Abstract) Bull. Geol. Soc. Amer. 13: 521, 1901.
[60] Footnote 43, p. 193.
[61] Footnote 25, Plate 17A.
[62] See footnote 30, pp. 797–799, Fig. 70.
[63] See footnote 39, Plates 7, 8, 10, 11.

One of the most striking results of later small veinlets across early carbonates is a *phantom vein.* The phantom vein is ordinarily clear carbonate, and is visible in plain light, crossing a more dusty carbonate (Figs. 3, 45, 49). When the nicols are crossed, it is found that the late carbonate is oriented crystallographically by the carbonate in the walls of the fracture; the crystals in the walls are "healed" by the growth of carbonate in the vein. The interference colors are so striking that the dustiness of the walls no longer catches the eye and the vein has disappeared like a phantom (Figs. 46, 49). In one sense this growth that heals the earlier crystals is a *"secondary growth,"* but it is rather different from the enlargement of sand grains in a quartzite. The phantoms may appear in any of the several colorless carbonates. They have been noted crossing calcite veins, calcite metacrysts in slate, siderite granules, and metacrysts in iron-bearing rocks (Fig. 49) and various other rocks. Ransome [64] shows siderite veins crossed by phantom veins, identified as ferrodolomite by B. K. Haffner. The phantom carbonate is accompanied by galena in the Couer d'Alene district; and by sulphide ores at Embreeville, Tennessee.

As systems of parallel veins grade into some with imperfect regularity they may be considered as involving inclusions of country rock in a vein. "Horses" of rock are usually large; but small veins may have inclusions that are relatively if not actually large (Figs. 44, 47). At an extreme, the abundance of inclusions means that the vein itself grades into the *cement of a breccia* (Fig. 48). Wells and Waters [41] show that carbonate veinlets "riddle an andesite."

Two or more Carbonates in a Vein.—The occurrence of two carbonates in a vein is commonly noted by differences in color or by chemical tests. In thin sections the copper carbonates are green or blue, those of iron brown on the oxidized borders—almost black if manganese is present.

A more general distinction when color does not serve is the contrasting relief in the several carbonate minerals even intergrown in a single vein (Table I). In many ores a carbonate vein of high relief is crossed by one of low relief (Figs. 29, 41). In the gold veins of Grass Valley, California, siderite veins are crossed by calcite.[65] Few examples are at hand of a vein of low relief crossed by a carbonate vein of high relief, but the reworked carbonate in the rock of Gibralter may have a dolomite later than calcite (Fig. 50), and the marble at the helvite prospect, in New Mexico, has such a vein, not easily photographed. A few examples have been reported elsewhere. Ross [66] found siderite cutting calcite at Fontana, North Carolina, and cites two other districts where siderite replaces calcite.

Two carbonates have been recognized in many veins. Wells and Waters [67] found much calcite and some ankerite or siderite in the mercury ores of Oregon; and Krieger [68] found the same minerals in silver ores in Mexico. Ross [66] gives a good illustration of the difference in relief of two carbonates.

[64] Ransome, F. L., and Calkins, F. C., The geology and ore deposits of the Coeur d'Alene district, Idaho. U. S. Geol. Survey, Prof. Paper 62, 1908.

[65] Footnote 39, p. 36.

[66] Footnote 25, p. 88 and Plate 31.

[67] Footnote 41, p. 25 and Plates 6, 113.

[68] Krieger, P., Primary silver mineralization at Sabinal, Chihuahua, Mex. ECON. GEOL. 30: 1935, pp. 245–257.

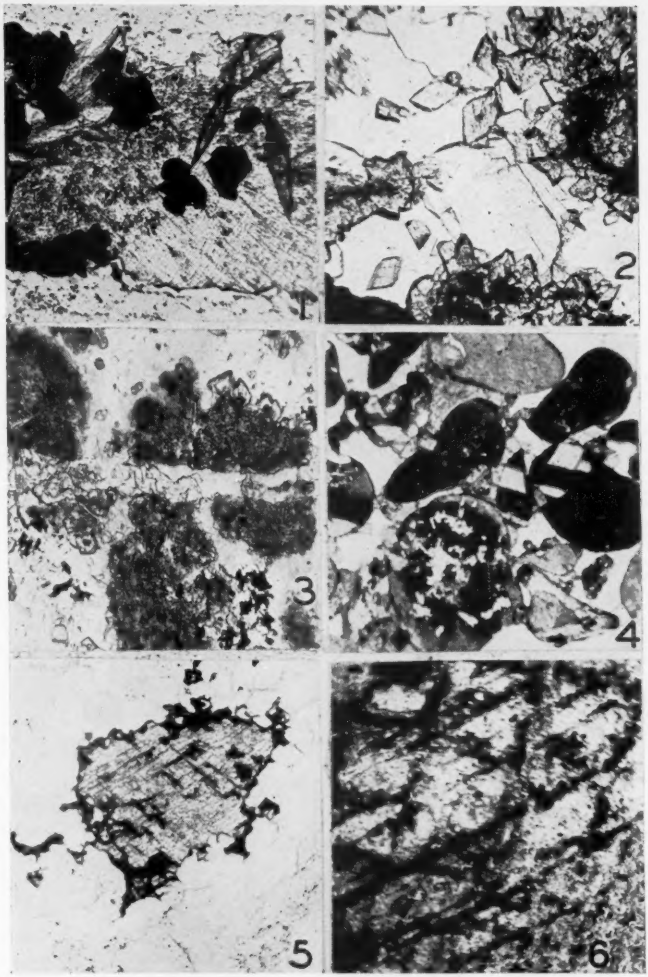

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FIG. 1. Two carbonates of different index (probably sideroplesite spindles in calcite) in a replacement vein with pyrite. Homestake ore, Lead, S. Dak. × 70.

FIG. 2. Two carbonates in a vein cutting opaque ores. The rhombs of high relief appear to be early, but are "unsupported," in the larger grains, of slight relief. Cananea, Mex. × 50.

FIG. 3. Dusty carbonate granules in chert, crossed by vein and partly replaced by carbonate in rhombs, not so dusty. Cuyuna Range, Minn. × 50.

FIG. 4. Greenalite granules and chert, partly replaced by siderite rhombs near a vein of chert and siderite. Mesabi. × 35.

FIG. 5. Ankerite with oxidized borders in quartz. Gold prospect, Minnesota-Ontario boundary. × 40.

FIG. 6. Carbonate with chert and brown stain emphasizing the cleavages. Pine City, Minn. × 40.

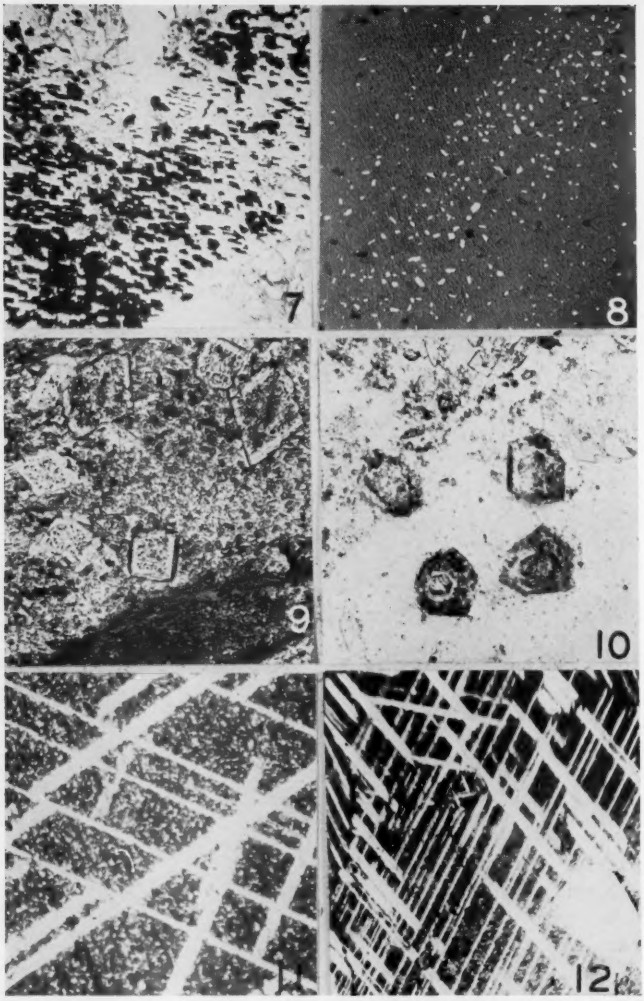

FIG. 7. Coarse carbonate replacing peridotite, rhomboid inclusions of magnetite. Cuyuna Range, Minn. × 20.

FIG. 8. Chalcocite inclusions along zones in calcite. Polished surface. Susie Island, Minn. Photo by G. M. Schwartz. × 50.

FIG. 9. Zoned carbonate metacrysts replacing schistose granule textured iron-formation near a carbonate vein. Cuyuna Range. × 50.

FIG. 10. Carbonate, cross sections of scalenohedra. Probably from Silver Islet, Lake Superior. × 25.

FIG. 11. Twinning in three directions in ankerite. Homestake mine, S. D. × 70.

FIG. 12. Twinning in three directions in dolomite. Chambishi mine, N. Rhodesia. × 60.

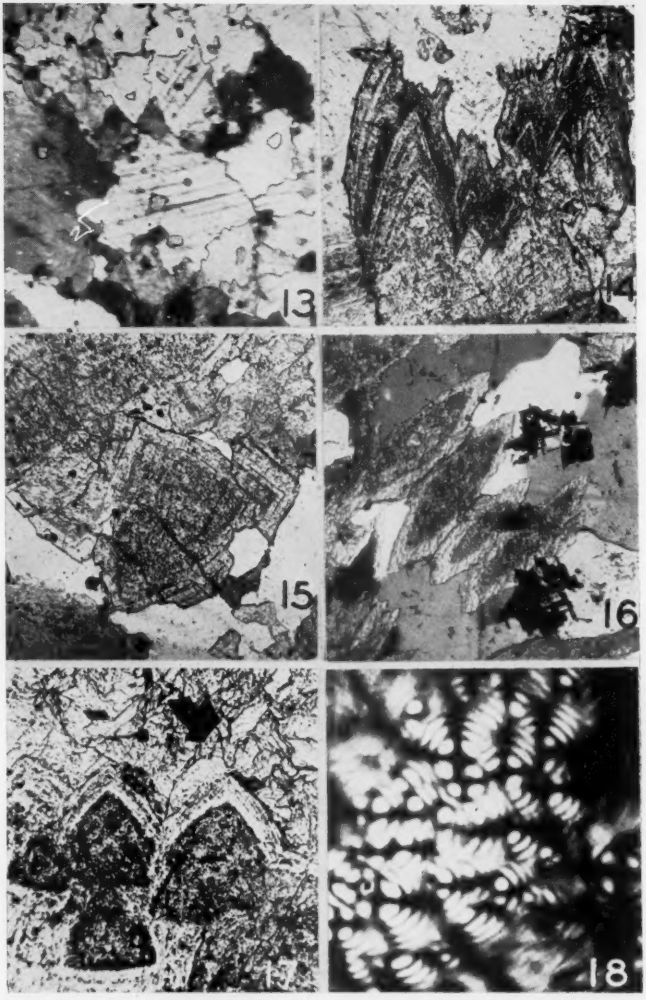

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FIG. 13. Calcite, sutured contacts, twinning, and poikilitic calcite inclusions, in helvite ores, New Mex. ×-nicols. × 55.

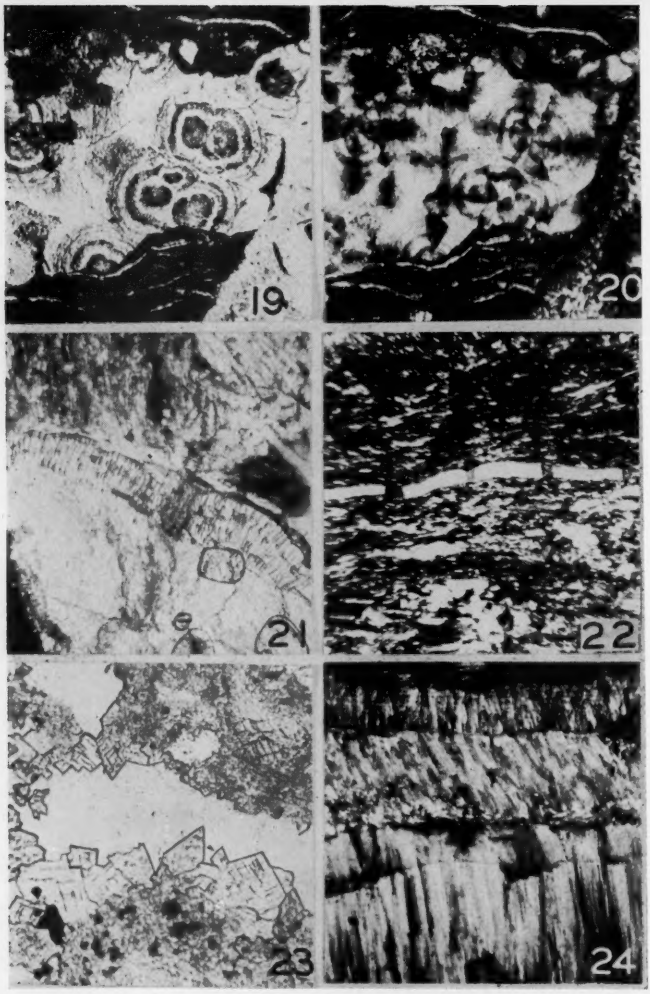
FIG. 14. Curved rhombs of calcite, boned resembling coxcomb, "Gothic arch." Holguin, Cuba. × 55.

FIG. 15. Curved rhombs of calcite, zoned; and quartz. Bannack district, Mont. × 70.

FIG. 16. Curved rhombs of sideroplesite, zoned, with quartz, pyrite and arsenopyrite. Photo by L. Lewis. Homestake mine, Lead, S. Dak. × 65.

FIG. 17. Manganiferous calcite, in curved rhombohedrons; and stibnite. Cleopatra mine. × 55.

FIG. 18. Interference cross from the field shown in Fig. 17, when nicols are crossed and focus changed; tube raised slightly. × 55.



FIGS. 19 AND 20. Twin photos, radial and concentric carbonates. Cuyuna Range. (19 plain light, concentric), (20 ×-nicols. Interf. cross shows radial). × 50.

FIG. 21. Feathered carbonate at one edge of crystal. Probably from Keweenawan of Minn. × 25.

FIG. 22. Coarse carbonate in a narrow opening looks "blocky." Parallel to schistosity of greenstone, near Geraldton, Ont. ×-nicols. × 40.

FIG. 23. Quartz filling vug in carbonate vein. Bannack, Mont. × 50.

FIG. 24. Fibrous carbonate and quartz, one band at a different angle from the rest. Promontoria mine, Mex. ×-nicols. × 15.

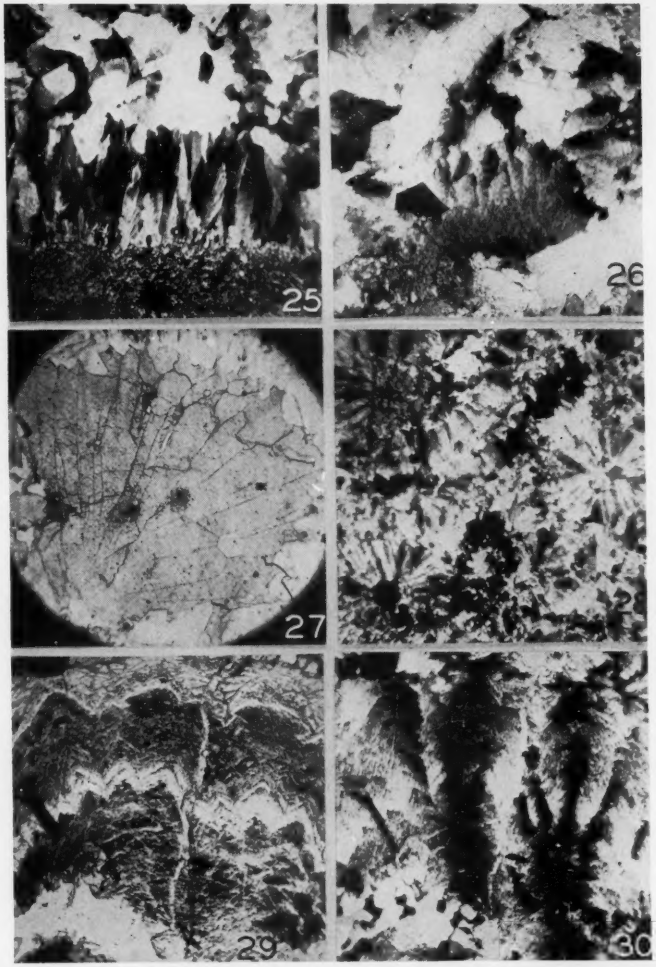


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FIG. 25. Comb structure in carbonate vein. Steep Rock Lake, Ont. ×-nicols. × 10.

FIG. 26. Flamboyant or comb structures in carbonate vein. Silver Islet. ×-nicols. × 50.

FIG. 27. Radial structure in vein carbonate, plain light. Wall Street, Col. Photo by L. Lewis. × 15.

FIG. 28. Radial to flamboyant structure in vein carbonate. Bannack, Mont. ×-nicols. × 35.

FIGS. 29 AND 30. Twin photos, curved rhombs of manganiferous calcite, coxcomb structure; 29 plain light; 30 ×-nicols, showing flamboyant structure. Cleopatra mine. The main carbonate is crossed by a carbonate veinlet of lower relief. × 30.

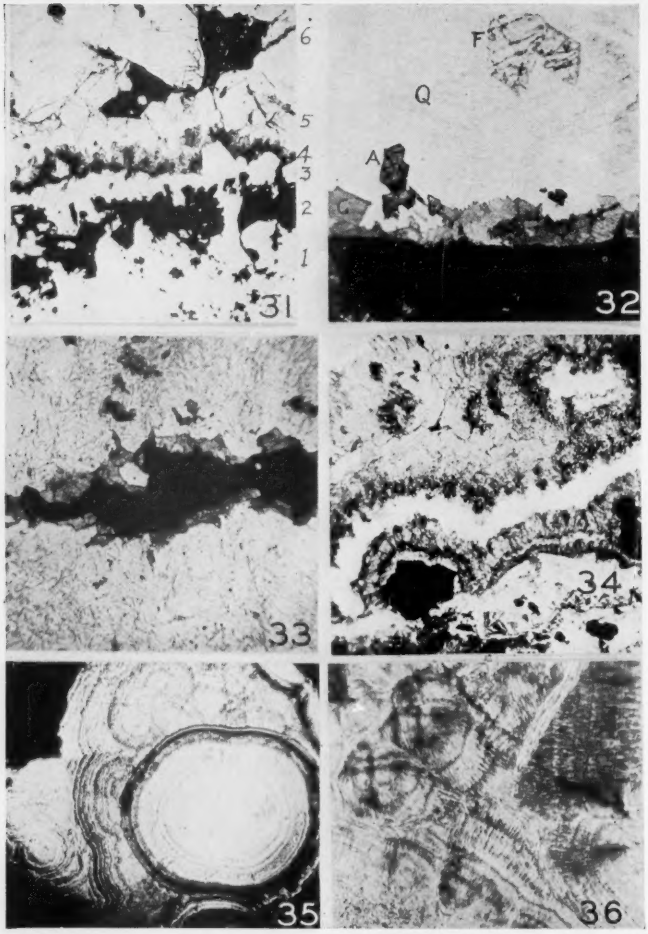

FIG. 31. Crustified vein. Bannack district, Mont. 1. Quartz; 2. Galena; 3. Quartz; 4. Carbonate; 5. Quartz; 6. Silver ores and quartz. Each grown on the crystals of the preceding crust. × 10.

FIG. 32. Vein and wall. Cuyuna Range, Minn. Wall of opaque ore. C. Rhodochrosite; A. Acmite; Q. Quartz; F. Adularia. × 10.

FIG. 33. Symmetrical vein, pyrrhotite center, sheath of carbonate, sides of quartz. Reno mine, Brit. Col. × 35.

FIG. 34. Curving crusts, resembling cockade ore, carbonate and quartz around sulphides. Bannack district, Mont. × 25.

FIG. 35. Colloform malachite, Clifton, Ariz. Polished surface. Photo by G. M. Schwartz. × 12.

FIG. 36. Metacolloidal malachite, thin section, Bannack district. × 120.

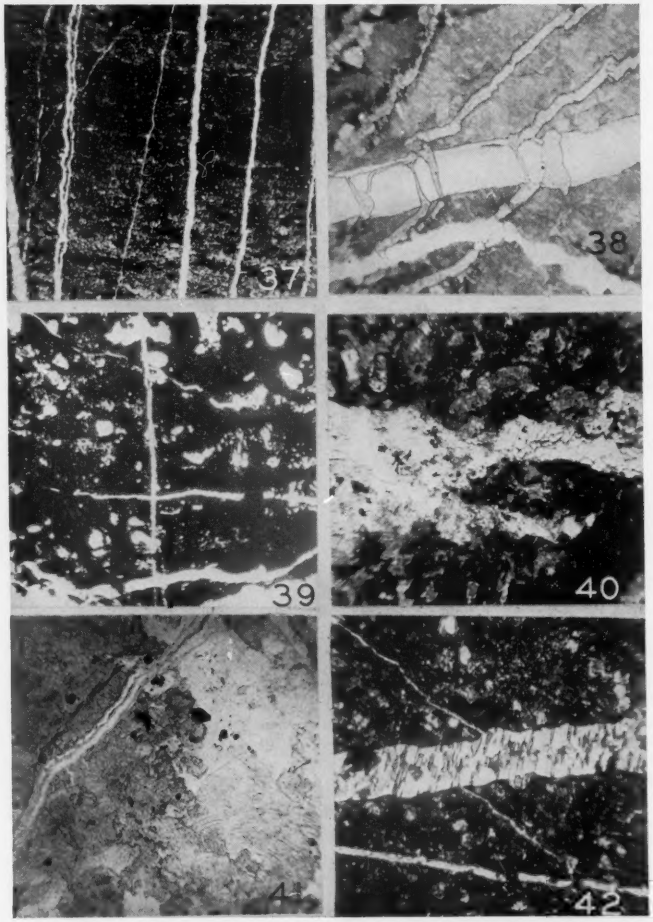

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FIG. 37. Parallel carbonate vein system, "book structure," in slate. Cuyuna Range, Minn. × 10.

FIG. 38. A series of nearly parallel carbonate veinlets in iron formation, change direction as they cross a hard quartz vein. Cuyuna Range, Minn. × 10.

FIG. 39. Coordinate carbonate veins. Cuyuna ore, Minn. × 20.

FIG. 40. Manganosiderite vein replacing iron formation. Cuyuna Range, Minn. × 20.

FIG. 41. Narrow carbonate vein cutting coarse, curved carbonate and quartz of early vein. Bannack district, Mont. × 30.

FIG. 42. Manganosiderite cross-fiber vein crosses and offsets an earlier smaller carbonate veinlet. Cuyuna Range, Minn. × 10.

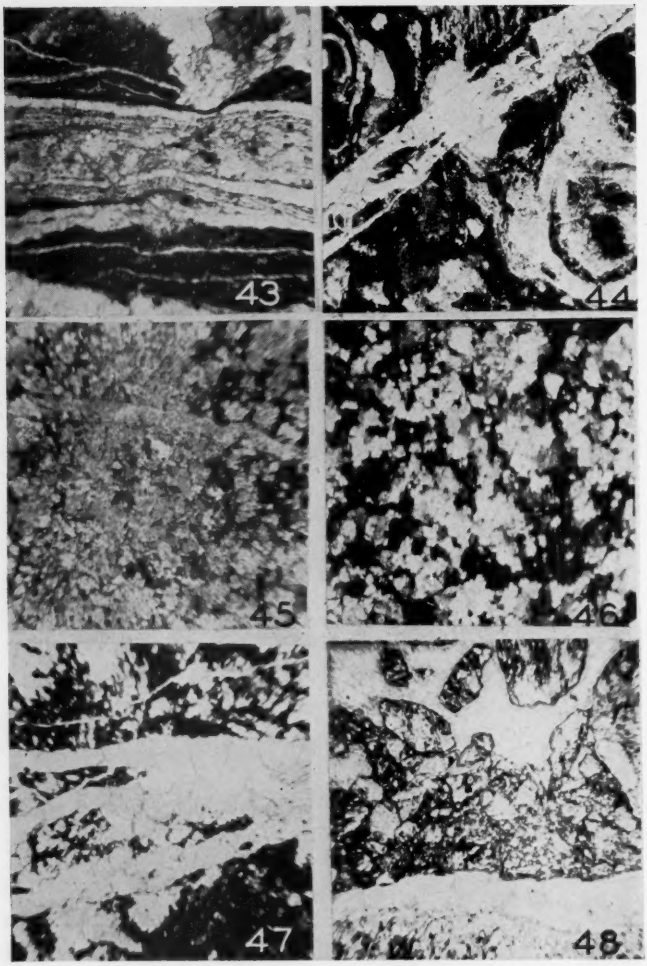

FIG. 43. Carbonate vein in slate, banded by reopening. Carlton, Minn. × 35.
FIG. 44. Quartz vein in oölitic cherty carbonate iron formation. Cuyuna Range. Some fragments of wall rock resemble vein carbonate. × 35.
FIGS. 45 AND 46. Twin photos of a phantom vein of carbonate. Mesabi Range, Minn. 45, plain light; 46, with crossed nicols, leaves the vein much obscured. × 18.
FIG. 47. Branching carbonate vein, and small "horse" of country rock, diabase. Cuyuna Range. × 10.
FIG. 48. Breccia, carbonate cement and carbonated fragments. Fine grained parts are essentially gouge. Ontario. × 10.

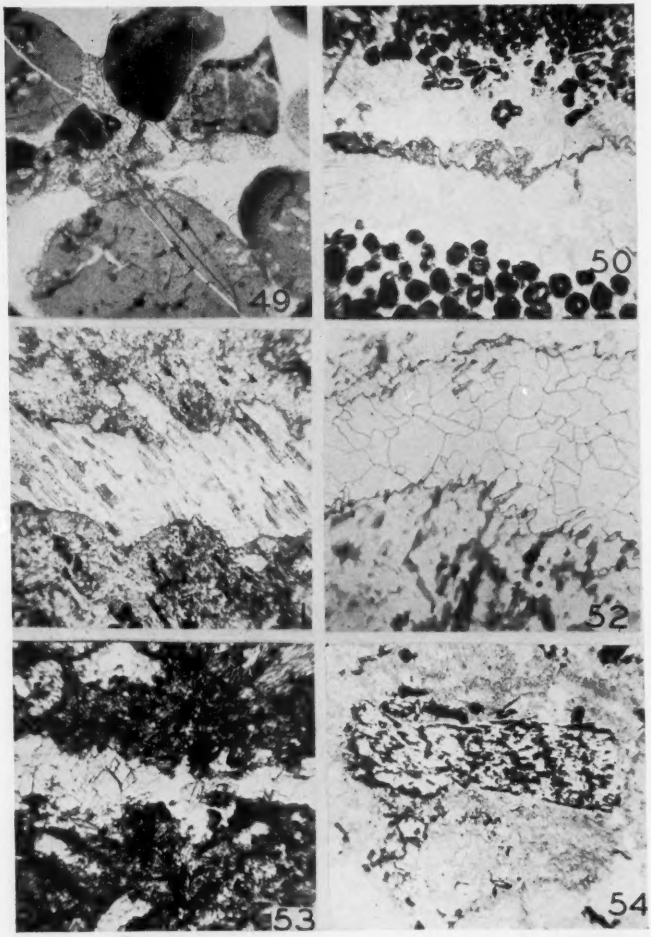

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FIG. 49. Phantom veinlets of siderite crossing metacryst of siderite in greenalite rock. Mesabi Range. × 45.

FIG. 50. Vein along stylolite, rearranging carbonate already present in oölite. Rock of Gibraltar. × 12.

FIG. 51. Cross fiber vein of calcite, with fibers parallel to schistosity of walls. The carbonate replaces the walls very irregularly. Long Lac, Ont. × 10.

FIG. 52. Carbonate vein of mosaic texture, partly replacing biotite schist, but finding biotite less easily replaced than other minerals. Ducktown, Tenn. × 17.

FIG. 53. Manganosiderite vein replacing granule-textured acmite walls. Cuyuna Range. × 20.

FIG. 54. Pseudomorph of carbonate after pyroxene. Matrix also carbonated, producing "pseudomorphous texture." Holguin, Cuba. × 20.

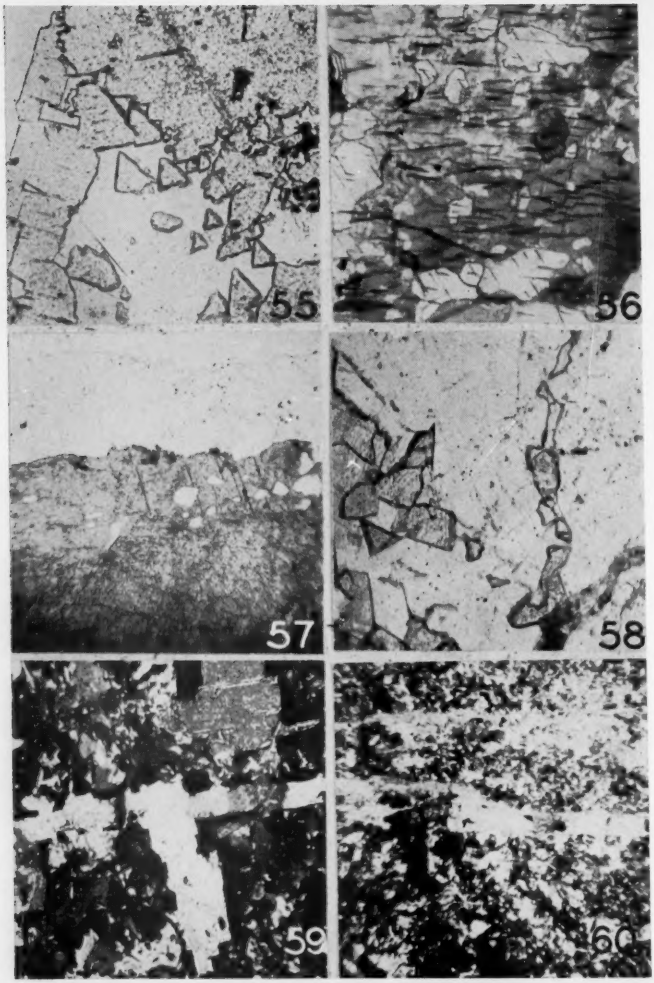

FIG. 55. Calcite and quartz in vein intergrowth showing mutual, crystal, oriented "islands," as if each replaced the other. Oatman, Ariz. × 15.

FIG. 56. Oriented islands of carbonate in actinolite, as if actinolite was late and replaced carbonate. Ducktown, Tenn. × 30.

FIG. 57. Oriented islands of vein quartz in carbonate vein, indicating replacement by carbonate. Tower, Minn. Photo by L. Lewis. × 35.

FIG. 58. Irregular veinlet of carbonate in quartz, and euhedral carbonate replacing quartz near the veinlet. Bannack, Mont. × 45.

FIG. 59. Carbonate cuts groundmass and replaces phenocrysts more widely. ×-nicols. Near Geraldton, Ont. × 50.

FIG. 60. Carbonate veinlets are separate, but the rock between veinlets is mostly replaced. Butte, Mont. × 50.

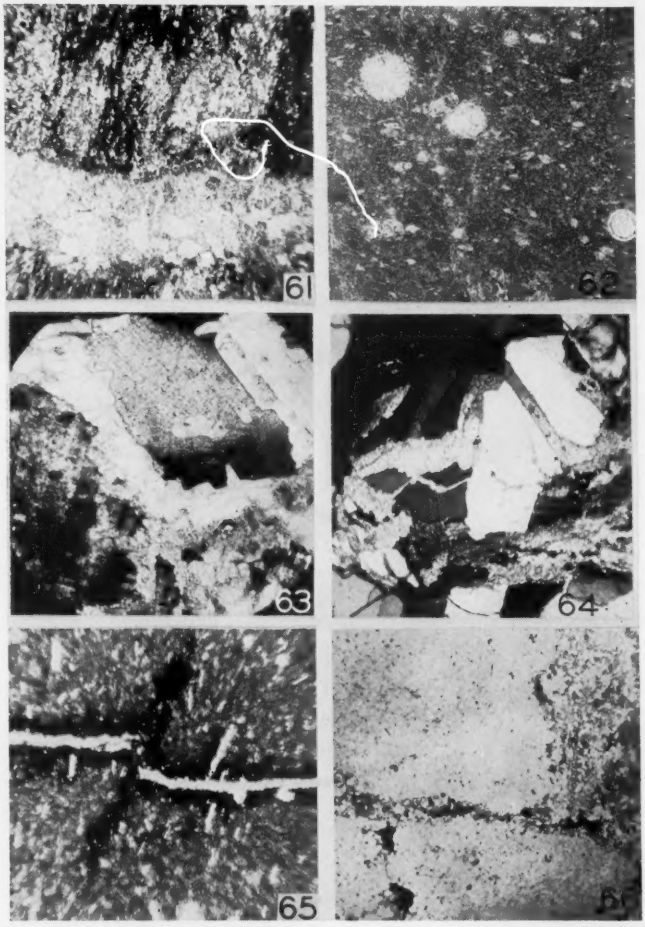

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FIG. 61. Mosaic vein crossing chlorite schist, and replacing schist irregularly, mostly within a distance about equal to the width of the vein. Steep Rock Lake, Ont. × 8.

FIG. 62. Carbonate replacing radiolaria near minute carbonate veinlets. Jalisco, Mex. × 30.

FIG. 63. Carbonate replacing zoned orthoclase, in a copper deposit prospected by W. H. Weed. Photo by L. Lewis. × 35.

FIG. 64. Carbonate veinlets cut early quartz and darker feldspar, replacing feldspar more widely. Pine City, Minn. ×-nicols. × 20.

FIG. 65. Carbonate filling in faulted vein; and pyrite replacement of the walls of the vein and fault. Cerralvo, Mex. × 30.

FIG. 66. Carbonate veinlet grades into disseminated replacement of quartzite. Couer d'Alene, Ida. × 8.

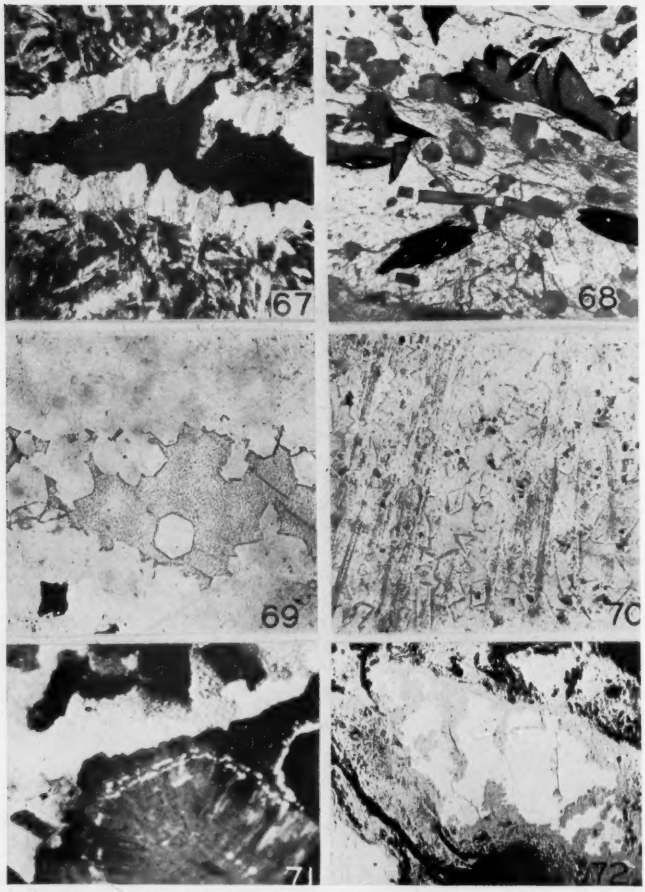

FIG. 67. Quartz and carbonate intergrown in a comb structure, galena filling the vug. Cerralvo, Mex. × 30.

FIG. 68. Chlorite schist mineralized by specularite and tourmaline, and then largely replaced by ankerite. Gold prospect, Rainy Lake, Minn. × 35.

FIG. 69. Quartz vug, carbonate filling. Wall Street, Col. × 30.

FIG. 70. Calcite wholly replaced. Quartz blades first followed calcite cleavages. Quartz and adularia then replaced the rest of the carbonate leaving the early blades dusty. Oatman, Ariz. × 45.

FIG. 71. Feathered and zoned quartz replacing carbonate that was granular. The white inclusions in the quartz are carbonate oriented as in the grain above. Butte, Mont. × 25.

FIG. 72. Malachite (gray) replacing chalcocite (white). Polished surface. Washoe County, Nev. Photo by G. M. Schwartz. × 12.

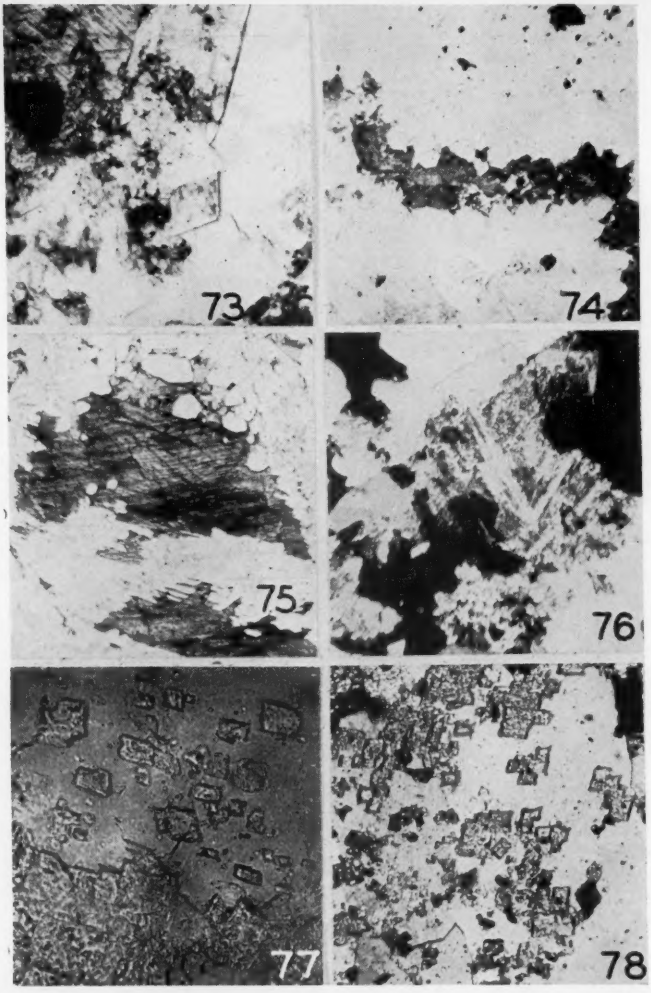

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FIG. 73. Carbonate at the upper left, quartz at the bottom. A carbonate rhomb near the center has been wholly silicified to form a pseudomorph. Bannack, Mont. × 50.

FIG. 74. Crustified vein, crusts attacking earlier crusts. Carbonate, in the dark crust, attacked the earlier quartz and was attacked by later quartz. Wall Street, Col. × 15.

FIG. 75. Calcite, dark, partly replaced by quartz, leaving blades and forming oriented partly euhedral "mutual" islands of each mineral; some euhedral quartz. Oatman, Ariz. × 15.

FIG. 76. Zoned carbonate partly replaced by quartz without quite destroying the zones. Silver Islet. × 50.

FIG. 77. Chert replacing carbonate leaving oriented rhombic islands of carbonate. Mesabi Range. × 200.

FIG. 78. Carbonate partly replaced by coarse quartz, leaving rhombic islands. Zacatecas, Mex. × 45.

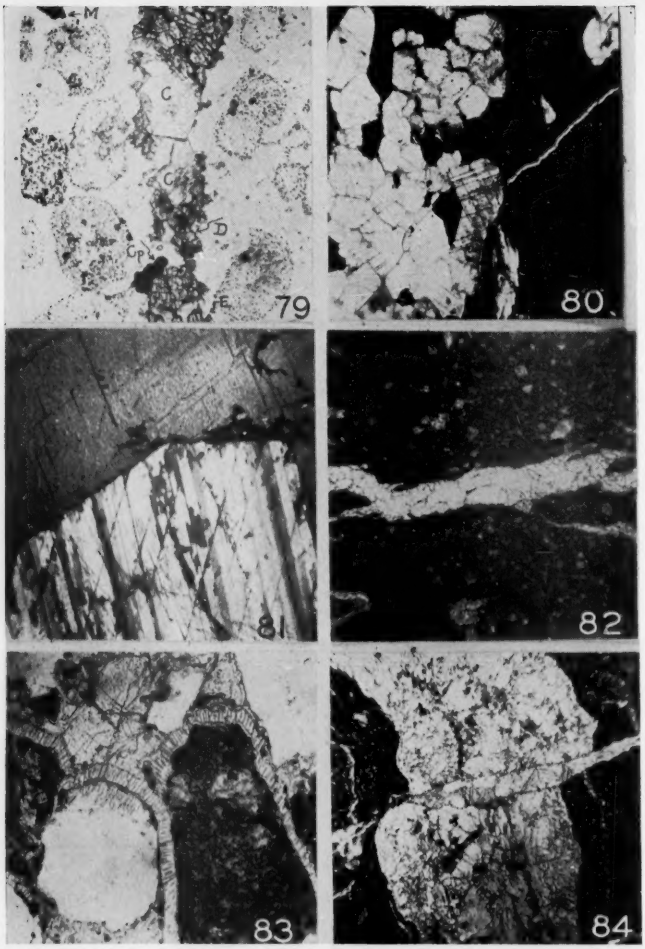

FIG. 79. Carbonate in hypothermal veinlet, crossing granule-textured chart. Mesabi Range. C, calcite; D, diopside; E, epidote; G, garnet; Cp, chalcopyrite; M, magnetite. × 40.

FIG. 80. Late carbonate veinlet cuts pyrrhotite that cuts and replaces early coarse carbonate and actinolite. Ducktown, Tenn. × 18.

FIG. 81. Calcite, zoned, with twinned core, partly replaced by native copper (black). Mich. × 10.

FIG. 82. Carbonate vein branching in carbonate walls. Minneapolis, Minn. × 18.

FIG. 83. Cross fiber veins (or cement) with fibers radial around pebbles. Cal. × 30.

FIG. 84. Carbonate vein in slate, faulted. The fault opening is filled with later carbonate. Carlton, Minn. × 10.

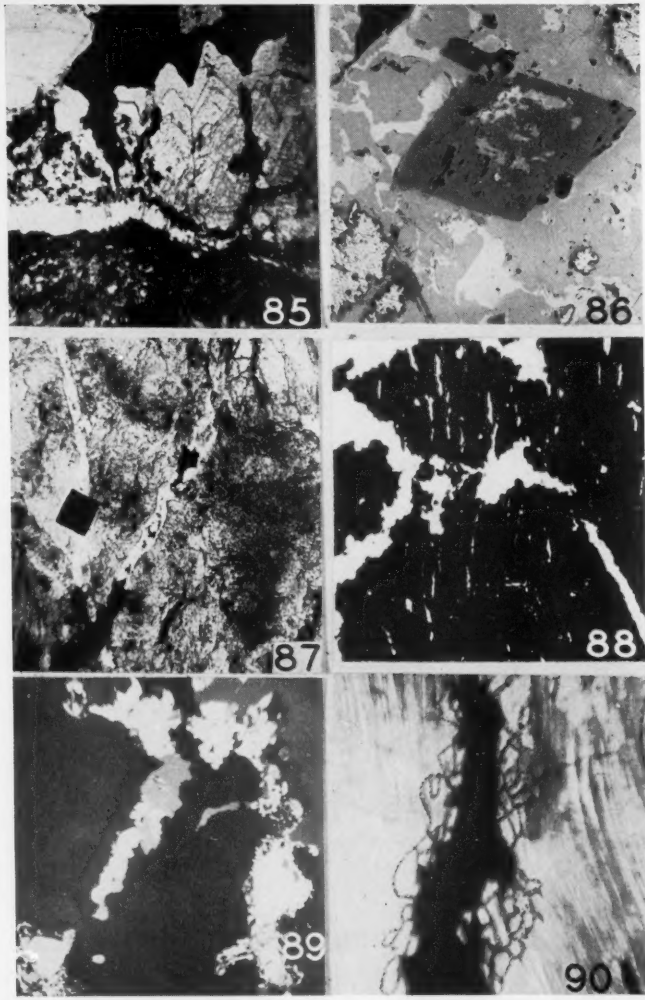

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FIG. 85. Calcite, zoned, partly replaced by chalcocite. Michigan. × 30.

FIG. 86. Carbonate in Bisbee, Ariz., ore: chalcocite (white), bornite (light gray), carbonate (dark gray rhomb). Polished surface. Photo by G. M. Schwartz. × 100.

FIG. 87. Dolomite, dusty, cut by veinlets of cinnabar, fine quartz and pyrite. California. × 50.

FIG. 88. Carbonate cutting and replacing pyrrhotite that was deposited in limestone. Carolina, Mex. × 45.

FIG. 89. Carbonate veinlets cutting native antimony. West Gore, Nova Scotia. × 10.

FIG. 90. Vein carbonate, bent and granulated, and mineralized by pyrrhotite where broken. Ducktown, Tenn. × 50.

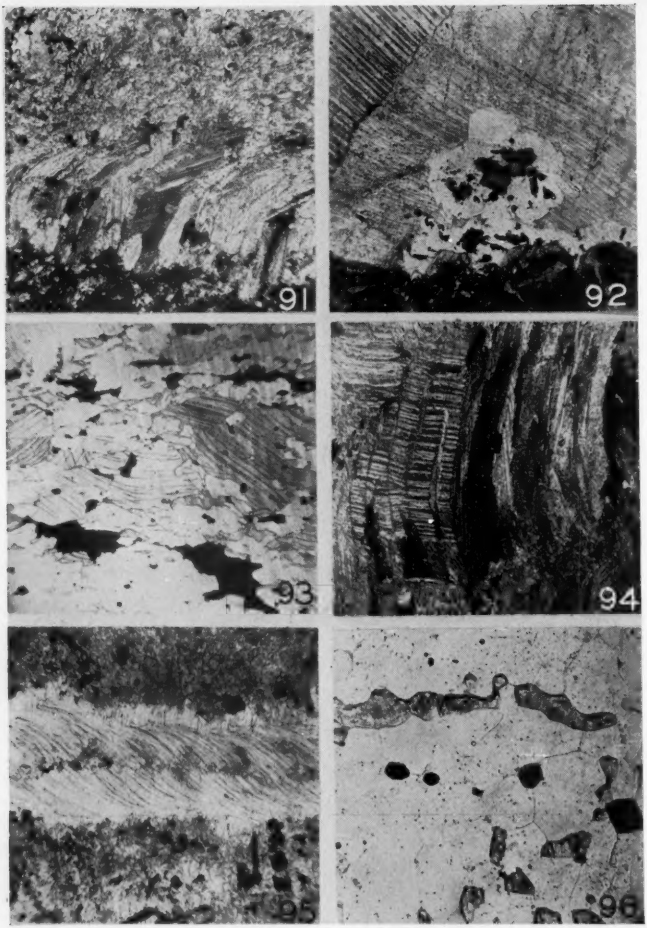

FIG. 91. One wall of a cross-fiber vein, showing the fibers bent, and ultimately granulated. Near Geraldton, Ont. ×-nicols. × 30.

FIG. 92. Carbonate amygdule, twinning bands deformed and curved. Partly replaced by copper (opaque), sericite (lighter), and epidote. Michigan. × 30.

FIG. 93. Carbonate oriented in schist by deformation. Ducktown, Tenn. × 10.

FIG. 94. Vein carbonate "shredded" by deformation. Near Geraldton, Ont. ×-nicols. × 30.

FIG. 95. Cross-fiber carbonate vein, with S-curve offset by deformation. Magnetite in the central parting and in wall rock schist. Near Geraldton, Ont. ×-nicols. × 30.

FIG. 96. Carbonate-quartz vein, with some pyrrhotite, appears to have been recrystallized to a texture resembling hornfels. Ducktown, Tenn. × 30.

Charlewood [69] says that in the Hollinger mine the difference in index is best tested in index oils, rather than depending on the relief in thin section.

Three or more carbonates are found in a number of veins, including Telluride, Colorado; [70] Tintic, Utah; [71] and the Couer d'Alenes, Idaho.[72] Emmons and Calkins [73] report that the ore at Philipsburg, Montana, carries calcite, dolomite (some ferruginous), siderite and rhodochrosite, besides secondary malachite, azurite and cerussite.

Influence of the Wall Rock.—It has been commonly observed from early studies of ores in veins, that veins may have gangue minerals related to their walls—where a continuous vein passes from a siliceous wall rock to a limestone the dominant gangue commonly changes from quartz to calcite. This was the basis of the old theory of "lateral secretion," but that is no longer an approved explanation. It is now common to assume that the vein filling liquid was approximately saturated with both minerals, and that the calcite wall stimulated calcite growth, whereas quartz in the wall stimulated quartz growth. This is indicated by the phantom veinlets already cited. A number of small veinlets in thin section have different fillings related to the walls of the opening (Figs. 3, 49). Fragments of carbonate wall in a vein may be mistaken for banded vein (Fig. 44).

Rearrangement of Carbonate.—Some carbonate veins, especially those formed at high temperatures and subjected to deforming pressures, may be rearranged and recrystallized. These resemble the material discussed in the next section as replacement; but since they remain the same mineral as before they are not true replacements. For example, Fig. 50 shows a vein along a stylolite in oolitic limestone; probably the vein material did not move far, and since the original rock and vein are both calcite it seems better to describe the process as a rearrangement than as a replacement. See also Figs. 90 and 91 illustrating deformation. Schistosity, hornfels, granulation, and suture patterns, all suggest recrystallization. The metacrysts (Fig. 9) with dusty core and clear rims may have lost the inclusions near the borders by a recrystallization. Adams [74] says of quartz veins that recrystallization tends to eliminate inclusions and dustiness; also that it is a much more common condition in hypothermal than epithermal veins. This is no doubt as true of vein carbonate as of vein quartz. The oolite structure in Fig. 50 above cited may have been marked chiefly by dust, which does not appear in the material reworked in the vein.

REPLACEMENT VEINS OF CARBONATE.

The classic papers by Lindgren [7] and by Irving [44] discuss metasomatism and the criteria for its recognition. They need no extensive review or discussion here, but it may be said that, since the clear descriptions in those

[69] See footnote 6, p. 504.

[70] See footnote 30, p. 789.

[71] Lindgren, W., and Loughlin, G. F., Geology and ore deposits of the Tintic mining district, Utah. U. S. Geol. Survey, Prof. Paper 107, 1919, p. 141.

[72] See footnote 43, p. 648.

[73] Emmons, W. H., and Calkins, F. C., Geology and ore deposits of the Philipsburg quadrangle, Montana. U. S. Geol. Survey, Prof. Paper 78, 1913, p. 157.

[74] Footnote 8, p. 652 and Plate 26.

papers, there has been general recognition of replacement veins. Several of their illustrations show carbonate replacing other minerals and various rocks. Lindgren notes fourteen principal vein associations showing metasomatism, of which four involve carbonates, namely gold-silver veins, mercury veins, dolomitic lead-silver veins, and sideritic lead-silver veins. It may be useful, however, to note briefly the main criteria which are still used and appear acceptable after the experience of intervening years.

Criteria of Replacement.—1. Partial pseudomorphs—visible secondary mineral occupying part of the area of a well-defined crystal of primary mineral (such as carbonate in a hornblende).

2. Complete pseudomorphs, where the forms characteristic of a mineral are occupied by a secondary mineral (Fig. 54).

3. Faceted crystals of a mineral, in a rock not of the same origin (such as rhombs of siderite in a granite).

4. Faceted crystals transgressing original structures, such as slaty cleavage or grain boundaries, or the boundaries of rounded pebbles (Fig. 4).

5. Retention of a structure or texture of a rock by an aggregate of different origin (such as an aggregate of granular carbonate in a schist, the carbonate having ghost-like remnants of undisturbed schist) (Figs. 51, 61).

6. Veins with walls that do not match, even by offset (Figs. 1, 40, 51, 52, 53, 72).

7. Excess of introduced material over the porosity of a rock (such as 50 per cent of pyrite in a sandstone).

8. Oriented, unsupported blocks, "islands," of the older material in the younger material (Figs. 56, 57, 77, 78). But note that at some contacts of two minerals each may contain oriented "islands" of the other (Figs. 55, 75) so that interpretation is not at all conclusive. For example, at Ducktown, Ross may have evidence as to which minerals were early and which later, but in the descriptions of his plates,[75] he seems to base his conclusions on oriented islands, whereas the plates show *mutual* inclusions—the intergrowth may well have originated by simultaneous growth.

Each of these criteria needs qualification and discussion, and Lindgren [76] notes that some of those commonly used are unsafe. If several agree the conclusion that there has been replacement is very strong. On the other hand the crustified banding and vugs of epithermal veins are commonly accompanied by no signs of replacement at all.

Features of Replacing Carbonates.—The most striking features of carbonate that replaces other minerals are the inherited features of the original materials—pseudomorphs and "pseudomorphous textures." The gold ores of Holguin, Cuba, have formed by replacement of altered peridotite; the basic silicates were almost 100 per cent replaced by serpentine and then the serpentine was replaced by gold ore in carbonate gangue; the original may still be identified in the ore by the pseudomorphs of carbonate after mafic minerals (Fig. 54) and by the scattered accessory chromite of the peridotite. Ransome [77] found calcite pseudomorphs after tremolite. Wells and Waters [41] show siderite pseudomorphs after the phenocrysts of an andesite. Ross [78]

[75] Footnote 25, Plates 2A, D, 14D, 15B, 16.

[76] Footnote 43, p. 209.

[77] Ransome, F. L., Economic Geology of the Silverton quadrangle, Colo. U. S. Geol. Survey Bull. 182, 1901, p. 72.

[78] Footnote 25, Plate 7A.

shows calcite replacing parts of the plagioclase grains of a pegmatite. Almost as commonly, however, carbonates may develop euhedral crystals (Figs. 4, 58), and even zoned crystals (Fig. 9) by replacement; this is rather in contrast to the common replacements by quartz, which are anhedral except in some soluble rocks like limestone. Finally there are the very common irregular replacements in which the sides of the vein do not match (Figs. 1, 40, 51, 52, 53, 72). Several veins cross schist and replace some layers farther than others (Fig. 61). Gel replacements may produce rounded concentric colloform structures; as at Cobalt, Ontario;[79, 80] and at many copper deposits, where sulphide ores are replaced by carbonates in the oxidized zone (Figs. 35, 36). Colloform malachite replaces chalcocite in Washoe County, Nevada.

Almost all the carbonates are known to replace other minerals.[81] Perhaps the manganese carbonate is least often noted in the literature of replacement, but there are examples (Fig. 53).

Almost all of the common rock minerals and a good many ore minerals have been recorded as replaced by carbonates. Lindgren[81] notes occurrences of about a dozen minerals. Ross[25] gives about 60 illustrations of carbonate relations, one-third of which are said to involve replacement. The list is perhaps so lengthy as to have little value except in emphasizing how universally carbonates are added by solutions. Rocks and ores of the greatest variety of origin and mineral nature may be carbonated. Schwartz[82] notes many examples of carbonation of igneous rocks.

Quartz is rather refractory, and other minerals are likely to be attacked in preference to quartz, but there are many evidences of its attack by carbonates. Fig. 74 shows the terminal quartz faces in a vug attacked by later carbonate. Veins of carbonate in cherty iron-bearing rocks replace the quartz in the walls and add rhombic grains to the chert near the veins (Figs. 4, 9). A Mexican chert with fossil radiolaria, which were undoubtedly silica as deposited, is now carbonated near some minute carbonate veinlets (Fig. 62). The carbonated forms are more easily recognized than the siliceous ones farther from the veins. Lindgren[82a] records that calcite replaces quartz and may project into it in rhombohedral facets; siderite also can replace quartz and produce faceted crystals. Ferguson and Gannett[45] show zoned euhedral ankerite replacing granite, and carbonate replacing the quartz of breccia. Ransome[83] shows siderite replacing quartzite in the Couer d'Alenes, and galena in cracks in the siderite.

The common silicates, feldspars and mafic minerals, are readily replaced by carbonates (Figs. 54, 63). The literature contains many examples.[84] See the preceding notes on pseudomorphs. The calcium silicates in contact metamorphic zones are replaced by calcite along late fractures. Greenalite

[79] See footnote 53, p. 9.

[80] Bastin, E. S., Silver ores of South Lorraine and Cobalt, Ontario. Econ. Geol. 20: 1–24, 1925, Plates 2, 3; p. 11.

[81] See footnote 7, pp. 601–619.

[82] Schwartz, G. M., Hydrothermal alteration of igneous rocks. Bull. Geol. Soc. Am. 50: 181–238, 1939.

[82a] See footnote 7, pp. 605–607; Figs. 6, 13, 15, 18.

[83] Footnote 64, Plates 9, 13.

[84] Footnote 7, pp. 605–607.

of the Mesabi iron-bearing rocks is cut by euhedral siderite (Fig. 4). Serpentine is commonly replaced by dolomite or by magnesite, as evidenced by veins the sides of which do not match.[85]

Igneous rocks with a variety of minerals are subject to replacement by carbonate along the walls of hydrothermal veins. Johnston [39] finds the carbonation of granodiorite at Grass Valley occurred early, and the carbonate was itself later replaced by sericite, and that by quartz. Wells and Waters [41] show that andesite, crossed by fissures containing siderite, is also replaced by disseminated siderite.

Finally there are examples of carbonates replacing other carbonates. Dolomite in veins in limestone replaces the calcite in the walls.[86] (The more widespread dolomitization of limestone by sea water is not included in this study of veins.) Dolomitization is said to be more active along hypothermal than along epithermal veins.[87] A high proportion of malachite occurrences seem to be replacements of limestone.[88] Lindgren [89] generalizes that limestone can be replaced by dolomite, siderite and smithsonite; and vein calcite is similarly replaceable.

A noteworthy feature of carbonate replacement is that it is selective. Where the fracture crosses several minerals the vein matter may replace one more widely than another (Fig. 64). Ross [90] gives an excellent example of calcite crossing actinolite and zoisite, showing that the vein is much wider in the zoisite.

Vein Filling Associated with Wall-rock Replacements.—Carbonate vein fillings show a wide range of different relations to the replacements of their walls. Many veins involve no appreciable replacement (Figs. 22, 37, 41, 84). Others show a fairly complete replacement of the walls for a short distance from the fracture and not much beyond (Fig. 61). Still others fill sharp walls for part of their course, and, especially, where the vein breaks up into minute stringers, they merge into replacements in which no fracture is appreciable (Fig. 66). Others still are closely spaced so as to constitute a shear zone, and the rock between fractures is fairly uniformly carbonated the whole width of the zone (Fig. 60).

Examples of replacements grading into veins are noted in textbook citations of contact deposits transitional to hypothermal veins. Spurr [91] reports pegmatite vein-dikes grading into contact rocks and believes ores do the same. In the Allegheny district, California, most of the carbonate is later than the quartzose ore, and not only fills fractures but replaces the quartz.[45]

It is common to find that mineralization adds one mineral (or group) replacing the wall rock and a different mineral (or group) in open spaces. In some Wisconsin veins the lead and zinc ores accompanied by calcite fill openings, but pyrite replaces the (dolomite) walls. The Embreeville district in

[85] Footnote 12, p. 142; Fig. 46.
[86] Footnote 36, p. 111.
[87] Footnote 7, p. 606.
[88] Footnote 12, p. 140; Fig. 42.
[89] Footnote 43, p. 197.
[90] Footnote 25, Plate 28B.
[91] Footnote 11, pp. 725–729.

Tennessee has similar veins and minerals. At Cerralvo, Mexico, a faulted carbonate vein in limestone has walls replaced by pyrite (Fig. 65). At the Reno mine, British Columbia, a gold quartz vein-filling with only traces of carbonate has tremolite walls much carbonated. Lingdren [92] noted that, at Ophir, California, the gold-silver quartz veins fill openings, while the walls are carbonated; but in his *Mineral Deposits* (p. 662) found that carbonate-filled fissures might occur in walls of silicified limestone. He also notes (p. 742) that tin veins in Akenobe have siderite replacing their walls, but no siderite fills the open spaces. Knopf [93] found that along the Mother Lode quartz is the chief fissure filling, but that carbonate (ankerite) and not quartz replaces the walls. Emmons [94] found that in the Tenmile district, Colorado, a barren vein filling of calcite in the Queen of the West mine had galena, sphalerite, and silver, replacing its walls. Bain [95] reports that Kirkland Lake quartz veins with high gold values have walls partly carbonated and with pyrite and tourmaline. Lindgren [95a] after recording that many gold veins with quartz and pyrite filling have walls replaced by sericite and calcite, summaries such effects in general with the remark that some wall rocks act as a semipermeable membrane.

SUMMARY OF RELATIONS OF VEIN CARBONATES TO GANGUE AND ORE.

Criteria of Paragenetic Sequence.—Paragenetic sequences involving carbonates are reported from a large number of ore deposits. The criteria for determining sequence are different for fillings and for replacements, but both have been discussed at some length and in most cases a few simple features give reliable evidence. In a complex ore there may be conflicting evidences and plenty of chance for disagreement as to the true sequence of mineral formation.

The most useful points are clearly:

1. A vein is later than its walls, even if the fractures are small, or run into mineral cleavages.
2. The center of a symmetrically banded vein is later than material near sides (Figs. 33, 67). Vug fillings are later than the crystals lining the vugs.
3. A crust of late mineral lies on euhedral tips of crystals of an earlier crust (Figs. 32, 34).
4. Epigenetic minerals (defined as later than the origin of the rock); hydrothermal minerals in an igneous rock, and pyrite in a sandstone are necessarily epigenetic.
5. A comparison with commonly observed sequences elsewhere in veins of similar minerals. Add the theoretical consideration that commonly low temperature minerals disappear if temperatures increase, whereas high temperature minerals may persist and be only cut or partly replaced by later minerals at lower temperatures. (The crystalloblastic order in metamorphic rocks refers to the tendency to develop euhedral metacrysts, and not to a time sequence.)

[92] Lindgren, W., The gold-silver veins of Ophir, Calif. U. S. Geol. Survey, 14th Ann. Rept., II, 243–284, 1894, p. 278.

[93] Knopf, A., The Mother Lode system of California. U. S. Geol. Survey, Prof. Paper 157, 1929, pp. 44–45.

[94] Emmons, S. F., Tenmile district special folio. U. S. Geol. Survey Folio 48, p. 5, 1898.

[95] Bain, G. W., Wall rock mineralization along Ontario gold deposits. ECON. GEOL. 28: 706–743, 1933.

[95a] Footnote 43, p. 196.

6. In replacements, faceted crystals cutting across recognizable structures, are later than the minerals that were involved in the structure.
7. A pseudomorph is later than the mineral whose form it has.
8. "Pseudomorphic texture" shows that present minerals are later than those producing the textures now seen only in relicts.

Ross [96] gives a considerable discussion of these and half a dozen other criteria, noting that several are unreliable.

Relations of Carbonate with Quartz and Chalcedony.—The two most common vein minerals are calcite and quartz and they are associated intimately, and commonly, and in a variety of relationships. Both are ubiquitous. Not all relationships can be shown here, and some may even be overlooked, in the abundance and complexity of the associations. There are comb structures in which "teeth" of quartz alternate with those of carbonate in evidently simultaneous growth (Fig. 67). Replacement fringes of quartz and carbonate around metacrysts of pyrite are analogous, but probably did not grow in large openings. Vugs lined with quartz crystals are commonly filled with later carbonate (Fig. 69) and vugs lined with carbonate crystals may be filled with later quartz (Fig. 23). The crustified banded veins may show alternating layers of quartz and carbonate (Fig. 31). Some early carbonate is cut by later veinlets of quartz (Fig. 87), in many crystals the quartz following the calcite cleavages (Fig. 6). On the other hand early quartz is commonly cut by later veinlets of carbonate (Fig. 64). A single vein may be reopened, or fractured repeatedly, so that quartz and carbonate may each be deposited at more than one period, more or less in alternation. Quartz may replace carbonate even forming pseudomorphs (Fig. 73), and carbonate may replace quartz (Figs. 66, 74). Replacements preserving original structures and some developing new structures have already been noted.

One of the most striking illustrations in Irving's paper [97] shows a thin section of silicified dolomite in which the original structure of zoned rhombs can still be clearly recognized. At Oatman, Arizona (Fig. 75), carbonate is early in gold ores, and is partly replaced by quartz before the ore came in. Adams [98] and Ransome [99] show pseudomorphs of quartz after calcite blades (some curved). The lamellar quartz may persist after all the rest of the calcite is replaced by quartz (Fig. 70), leaving a "retiform" structure or net of blades in a fine granular field. See also Lindgren and Bancroft; [100] and Platts.[128]

Graton and McKinstry [120] found gold in veinlets cutting ankerite and even running into cleavages of ankerite crystals; and the ankerite was replaced by quartz leaving gold in quartz preserving the ankerite pattern.

Under certain conditions the replacing quartz develops euhedral crystals (Fig. 75) instead of an aggregate showing the rhombic form of the earlier carbonate. Berg [100a] shows euhedral quartz replacing ankerite. It is note-

[96] Footnote 25, pp. 8–16.
[97] Footnote 44, Plates 14, 15.
[98] Footnote 8, Plates 25, 26.
[99] Ransome, F. L., Geology of the Oatman gold district, Arizona. U. S. Geol. Survey Bull. 743, 1923.
[100] Lindgren, W., and Bancroft, H., The Republic mining district. *In* U. S. Geol. Survey Bull. 550: 133–166, 1914, Plate 15, p. 147.
[100a] Footnote 12, p. 43.

worthy that quartz replacing zoned carbonate may preserve traces of the early zones (Fig. 76); but a more remarkable structure is a zoned and feathered quartz replacing granular carbonate that was not originally zoned (Fig. 71).

Chalcedony is also a common replacement of carbonate (Fig. 77) especially in the cold water and epithermal veins.[100b] Both quartz and chalcedony, in replacing coarse carbonate may leave rhombic residual islands of carbonate (Figs. 55, 77, 78).

Relations of Carbonates with Each Other.—As noted above calcite may be an early vein mineral and its deposition may continue through a period of ore deposition to form tiny late veinlets. More commonly perhaps the early carbonates are of different composition.

In the Cananea copper ore, early manganosiderite and associated calcite cut and seem to replace galena and sphalerite (Fig. 2). In the Black Hills ores a carbonate of low relief is later than sidero plesite (Fig. 1). Some Ontario veins show dolomite later than ankerite. Carbonates of calcium, iron and manganese are very commonly mixed in veins of ore [30] and all may be cut by late traces of calcite. In the Oregon quicksilver deposits a siderite vein is cut by a calcite vein.[41] In Arkansas and Missouri, calcite is later than dolomite in the veins of lead and zinc ore.[36, 100c] In Zacatecas silver veins, ferruginous carbonate is earlier than calcite.[101] Lindgren and Loughlin [102] report a series following the ore of the Tintic district, Utah, as: 1) dolomite, 2) calcite scalenohedrons, 3) calcite plates, 4) aragonite. Ferguson and Gannett [45] show clearly that in the Allegheny district, the carbonates formed at different times with different textures and the second one replaces the quartz that carries the ore. Ross [103] cites an observed sequence at Fontana, North Carolina. Spurr [104] gives several specific examples of mixed carbonates and later calcite, and then generalizes and gives a diagram. Lindgren [105] refers to carbonate successions at a number of districts and has generalized the sequence [106] showing quartz and calcite last.

Relation of Carbonates to Other Gangue Minerals.—A similar series of examples might be found to show the relations of carbonates to less abundant gangue minerals; replacements by carbonates are noted on a previous page; miscellaneous associates are fluorite; [107] barite; [42, 108] sericite; [41, 39] garnet.[109]

[100b] Footnote 8, p. 625.

[100c] Tarr, W. A., Origin of the southeast Missouri lead deposits. Econ Geol. 31: 712–754, and 832–866, 1936, p. 748.

[101] Bastin, E. S., Paragenetic relations in silver ores of Zacatecas, Mexico. Econ. Geol. 36: 371–400, 1941, pp. 398–399.

[102] Footnote 71, p. 159.

[103] Footnote 25, p. 54.

[104] Footnote 11, pp. 50, 51, 805, 810, 794–798.

[105] Footnote 43, pp. 501–502, 585, 698, 750–752, 754.

[106] Lindgren, W., Succession of minerals . . . in ore . . . . Am. Inst. Min. and Met. Eng., Tech. Pub. 713, 1936.

[107] Weller, Stuart, The geology of Hardin County, Illinois. Ill. Geol. Surv. Bull. 41: 257–275, 1920, Plate 115, Fig. B.

[108] Lindgren, W., Paragenesis of the minerals in the Butte veins. Econ. Geol. 22: 304–307, 1927.

[109] Lindgren, W., The copper deposits of the Clifton-Morenci district, Arizona. U. S. Geol. Survey, Prof. Paper 43, 1905.

The Minnesota collections show carbonate related to garnet (Fig. 79), chlorite (Figs. 51, 61), acmite (Fig. 53), adularia (Figs. 32, 70), and tourmaline (Fig. 68). Ransome [77] shows calcite earlier than quartz but later than fluorite.

Relations of Carbonates to Ore Minerals.—The first important relation under this heading is that several carbonates *are* ore minerals, notably in the zone of oxidation. This is especially likely if the primary ore carried carbonates or the wall rocks were limestones. Malachite, azurite, smithsonite, and cerussite may form large ore bodies [110] and commonly contribute a good deal to the secondarily enriched ores by filling fractures and replacing the gangue of sulphide ores. Fig. 72 shows malachite cutting sulphides of copper in Washoe County, Nevada. Schwartz [111] shows very well the relations of copper carbonates to other copper minerals; and Ross [112] shows malachite cutting chalcocite and covellite. There are also a few veins in which the primary carbonates siderite and rhodochrosite constitute ores—more or less impure with other ore and gangue minerals.[113]

As gangue minerals the vein carbonates are associated commonly with sulphide ores, native metals and less commonly with the oxides. Merwin [114] presents evidence of the simultaneous growth of calcite and certain sulphides of ore districts. Lindgren [115] gives specific sequences involving carbonates.

Chalcopyrite (Fig. 79) occurs with carbonate in hypothermal veins. McKnight [36] reports Arkansas lead-zinc ores have dolomite before chalcopyrite and calcite after it; and chalcopyrite is listed by Lindgren [108] at Butte as following some rhodochrosite but earlier than the ankerite, dolomite and calcite.

Chalcocite cuts and replaces calcite in some Keweenawan veins in Michigan (Fig. 85) and Minnesota, and it encloses and replaces carbonate at Bisbee, Arizona (Fig. 86), and forms zoned inclusions in calcite (Fig. 8) in Minnesota. Lindgren [108] reports calcocite at Butte later than all the carbonates (except the oxidized copper carbonates).

Cinnabar and quartz veinlets cut earlier vein dolomite (Fig. 87). Wells and Waters [41] find cinnabar with calcite and marcasite cementing a breccia.

Galena and sphalerite grew with calcite in veins in Wisconsin and Missouri, and with two carbonates in Cananea, Mexico (Fig. 2). The relations of these ores to carbonates are reported in detail from several districts; Bingham; [116] a British example; [42] Cripple Creek; [117] and Telluride,[30] where Purington notes at least a tendency for sphalerite to associate with rhodochrosite, in contrast to galena associated with calcite. Ransome [77] reports that at Silverton, calcite of late formation cuts the lead-silver ore minerals.

110 Footnote 33, Plates 49–52.

111 Schwartz, G. M., Paragenesis of the oxidized ores of copper. Econ. Geol. 29: 55–75, 1934.

112 Footnote 25, Plates 42, 43.

113 Collins, W. H., Quirke, T. T., and Thomson, E., Michipicoten Iron Ranges. Canada Geol. Survey Memoir 147, 1926.

114 Merwin, H. E., Simultaneous crystallization of calcite and certain sulphides. . . . Am. Jour. of Science 38: 355–359, 1914.

115 Footnote 43, pp. 482, 614, 683, 739, 646, 698, 672.

116 Boutwell, J. M., Economic geology of the Bingham district. *In* U. S. Geol. Survey, Prof. Paper 38: 73–396, 1905, pp. 118, 120, 160.

117 Lindgren, W., and Ransome, F. L., Geology and gold deposits of the Cripple Creek district, Colorado. U. S. Geol. Survey, Prof. Paper 54, 1906, p. 176.

Stibnite is intergrown with manganiferous calcite from the Cleopatra mine (Fig. 17). Both stibnite and realgar are associated with late calcite at Monte Cristo, Washington.[118]

Arsenopyrite is associated with carbonates in the Homestake (Fig. 16) gold ore, and in several Ontario gold ores. Other arsenic minerals are common with silver and calcite in Ontario.

Jamesonite is associated with calcite in Mexico, and may even be partly replaced by late calcite.

Pyrite occurs with other sulphides in perhaps half of all the ores with which carbonates are associated.

Pyrrhotite in the Carolina mine, Mexico, is cut and somewhat replaced by calcite (Fig. 88).

In summary, it seems clear that carbonates may be formed in veins both before and after the sulphide ores; but there is a general trend (not without exceptions) for the pre-sulphide carbonate to be mixed and complex, whereas the late carbonate is commonly calcite. The early carbonate is very commonly replaced by sulphide (Figs. 1, 85) whereas, the late calcite fills minute fractures (Fig. 80) and only rarely replaces much sulphide. Lindgren[119] and Bastin[119a] made this generalization a number of years ago, and there have been few exceptions noted in the intervening years. The large collections available for this study show a few examples of replacement of sulphide ores by carbonates; galena, pyrrhotite (Fig. 88), chalcocite, chalcopyrite and sphalerite (Fig. 2). Probably none of these replacements is extensive. The literature has some few examples—Ferguson and Gannett[43] show calcite replacing arsenopyrite. The generalization, of course, refers mostly to the carbonate gangue minerals, for as noted above (page 496) many carbonate ores result from oxidation and replacement of sulphide ores.

The native metals, gold, silver, copper and antimony are commonly enclosed in or associated with carbonates.

At Grass Valley, Johnston[39] reports gold with ankerite and along cleavage planes of calcite. At Holguin, Cuba, gold is associated with carbonate and quartz replacing a serpentinized periodite. Graton and McKinstry[120] report an inner zone at the Hollinger mine where gold is associated with ankerite and pyrite; outside of which there is more calcite and less gold. Mather[120a] finds at the Howey mine, Ontario, calcite is early and with the gold, but ankerite increased in proportion, later. Wright[121] reports gold in the cleavages of calcite in southeastern Manitoba. White[48] summarizes the relations of gold to its gangue in 27 American deposits; in early cataclastic quartz, possibly hydrothermal, the gold was deposited later: the carbonate associated with many of the ores began forming early and in small part continued even after

[118] Spurr, J. E., Ore deposits of Monte Cristo, Washington. U. S. Geol. Survey Ann. Rept. 22, II, 777–865, 1901, p. 837.

[119] Footnote 43, p. 199.

[119a] Bastin, E. S. Criteria of age relations of minerals. Econ Geol. 26: 588, 1931.

[120] Graton, L. C., and McKinstry, H. E., Outstanding features of Hollinger geology. Trans. Can. Inst. Min. and Met. 36: 1–20, 1933.

[120a] Mather, W. B., Geology and paragenesis of the gold ores of the Howey mine, Red Lake, Ontario. Econ. Geol. 32: 146, 1937.

[121] Wright, F. J., Geology and mineral deposits of a part of southeastern Manitoba, Canada. Can. Dept. Mines, Geol. Survey, Mem. 169: 54, 1932.

the deposition of gold. Schwartz [122] includes carbonates as common gangue minerals of gold and gives references to papers describing and illustrating them: Alaska, Juneau, ankerite; Michipicoten, Ontario, calcite; Cornucopia, Oregon, calcite; Oatman, Arizona, calcite; Uchi Lakes, Canada, calcite.

Carbonates are particularly characteristic as gangue minerals of silver ores, and include calcite, dolomite, siderite and rhodochrosite. The silver of Silver Islet, Lake Superior, is partly enclosed in calcite. Ellsworth [54] reports silver dendrites in calcite at Cobalt, Ontario, which have been described in several papers, Bastin [51] having suggested that silver was deposited at least partially at the same time as ferruginous calcite. The association of the copper of Keweenaw Point with calcite is also well known (Figs. 81, 92). The rare occurrences of metallic *antimony* seem to be in carbonate veins (Fig. 89).

The oxide ores such as *cassiterite* and *magnetite* are not commonly with carbonates in veins, but there are examples of carbonate-specularite veins (Fig. 68) and a few carbonate veins carry magnetite (Figs. 7, 95). Kennedy [123] shows magnetite veined and replaced by calcite. Siderite in cross-fiber veins is common at places in Mesabi hematite.

Complex Sequences Involving Carbonates.—Ross [25] studied a series of hypothermal deposits which, after mineralization at depth, were made complex by later events during cooling, metamorphism and erosion. He concluded (p. 9) that "dikes and veins are not in general the results of a single genetic process." The present writer after long experience with many simple veins in a variety of rocks questions whether any such conclusion applies "in general." Unless restricted to ores of the deep zone there is a high proportion of simple veins. Nevertheless the complexity of some good ores of the hypothermal class deserves a note.

The Ducktown "type" of ore studied by Ross has carbonate of two or more periods. There is an early dolomite, possibly of sedimentary origin. Some of the high temperature silicates, largely actinolite, formed before most of the vein calcite and some after. Only traces of calcite cut the ore, which is later than the actinolite.

A clear example of complex sequence of carbonates is that from Arizona where a contact rock has been hydrothermally attacked and veined. The original rock was evidently a limestone, and the second generation is the same material recrystallized with garnet and pyroxene. A second specimen is of the same rock with the pyroxene altered to a ferruginous carbonate—number three of the series. This specimen shows also a fourth generation of carbonate, in a veinlet cutting the carbonated pyroxene and matrix.

Another complex involving dolomite appears in a specimen from White Raven mine, Boulder County, Colorado. The rock is cut by a vein in which are chiefly quartz, barite, dolomite and galena; there is a late dolomite with comb structure, cut by later fine grained dolomite; and the final vug linings are curved flat rhombs of dolomite.

122 Schwartz, G. M., The host minerals of native gold. ECON. GEOL. 39: 371–411, 1944.
123 Kennedy, W. Q., Igneous rocks, pyrometasomatism and ore deposition at Traversella, Piedmont, Italy. Bull. Suisse de Mineralogie and Petrologie, vol. 11, pp. 76–139, 1931, pp. 128–129, Fig. 6B.

Many paragenetic sequences in ore veins include carbonate as a very early vein filling and calcite as one of the last veinlets cutting all other minerals. In a number of districts and even in a single complex vein, carbonate may have different associates, suggesting different temperatures or depths of formation. It is commonly said [124] that there are no laws of general application [125] because the series is influenced by the structure, texture, and minerals of the country rock, and by other factors. As a basis of expectation, however, Lindgren [126] has given a general paragenesis for hydrothermal and related deposits:

1. Several carbonates and quartz come before the ore minerals.[127, 128]
2. Oxide ores.
3. Pyrite, arsenides, etc.
4. Cassiterite, etc.
5. Pyrrhotite, chalcopyrite, etc.
6. Sphalerite . . . bornite, galena . . . gold.
7. Stibnite, cinnabar.
8. Calcite and quartz are latest of all.

THE DEFORMATION OF VEIN CARBONATES.

Brecciation (Fig. 48) may occur at almost any depth but is probably more likely to affect carbonates at shallow depths than great depths. Many early carbonate veins are crossed by later carbonate veins (Figs. 42, 84), indicating a period of shattering between the two. These should be sharply distinguished from branching veins (Figs. 40, 47, 82) which do not indicate a second period of deformation.

Pressure effects are commonly indicated by faulting (Figs. 65, 84) and by granulation of brittle minerals (Figs. 90, 91). Twinning may result from deformation. Adams [129] suggests that strain effects are probably early, on the theory that veins are rarely carried to depths greater than those at which they were deposited.

Many thin sections of vein carbonate show a bending of the grains and cleavages (Figs. 90, 91, 92, 93) very different from the curved growths and flamboyant crystals above described. It is probable that less stress is needed to bend calcite than to bend quartz. Bending and recrystallization (Figs. 91, 94) are characteristically hypothermal or deep seated effects.

Few carbonate rocks are schistose and, since many have been greatly deformed, it is commonly assumed that the carbonate loses its schistosity by reason of its solubility and easy recrystallization. Deformed carbonate veins may at places recrystallize even as marbles do. In a few veins, deformed carbonate is so mixed with quartz that the quartz has probably interfered with the later loss of schistosity. The mixed rock shows a notable parallelism (Fig. 93). Few of the purer carbonate aggregates have such a structure.

[124] Footnote 117, p. 175.
[125] Beck, R. (Translated by Weed, W. H.), Nature of Ore Deposits, 1909, p. 191.
[126] Footnote 106, pp. 10–11.
[127] Footnote 107, Plate 11F; footnote 8, Plate 25.
[128] Platts, J. B., Carbonate fissure veins. Eng. and Min. Jour. 127: 489, 1929.
[129] Footnote 8, p. 655.

Deep seated shearing across veins, however, does result in lenticular plates or "shredded" structures, more or less imbricated (Fig. 94). Some greenstone schists near Lake Abitibi, Canada, have veins of schistose carbonate, evidently deformed; also some cross-fiber veins, in which the fibers are parallel to schistosity. Adams [130] notes such structures in siderite. A moderate amount of motion may cause a "mortar" structure, of granulated bands across large crystals (Fig. 90). Shaly streaks in some limestone without much deformation, may slightly resemble schistosity.

Some carbonate veins, from districts of known deformation, show little sign of dynamic action. Possibly they have been recrystallized, as have the deformed marbles. One such vein (Fig. 96) has a texture suggesting a recrystallized hornfels.

The cross fiber veins commonly show an offset structure that can hardly be explained except as deformation. The offsets are angular in some but grade into S-curves in others (Figs. 24, 95). One such fibrous streak from Piney River, Virginia, shows diagonal carbonate fibers grading into chlorite fibers, both in an attitude parallel to the shear streaks and schistosity of the whole rock. Fig. 91 shows not only a pronounced bending of the fibers, but beyond the most extreme bending, a granulation. The evidence of deformation seems unusually clear.

DEPTHS AND TEMPERATURES OF CARBONATE DEPOSITION.

Emmons [131] summarizes the occurrence of carbonates in the several ore zones as follows: "ankerite, siderite, and calcite in hypothermal and mesothermal veins; and calcite, commonly manganiferous, and other carbonates in epithermal veins." He lists dolomite and calcite as known in veins of all classes from hypothermal to cold water sediments; dolomite deposition may be even a little more favorable than calcite as an associate for ores (p. 175). Cold water veins include, naturally, a number of carbonate ores of the metals—aurichalcite, azurite, cerussite, hydrozincite, malachite, smithsonite and others. Aragonite as a vein mineral is almost wholly a cold water deposit, though Wandke and Moore [132] list it as late in a very hot water vein. Rhodochrosite is rare in hypothermal veins, but siderite in a hot water vein suggests hypothermal rather more than epithermal deposition. Siderite is less common than ankerite in hypothermal gold veins, but siderite is more common in the lead-zinc deposits at high temperatures.[133] Ankerite in gold veins the world over appears to be earlier than the gold deposition,[133] and it seems that the proportion of ferrous carbonate in the carbonates of gold veins, increases with depth. Some of the reports of manganosiderite give evidence [134] that it is mesothermal, or transitional from that to hypothermal, and earlier than quartz and the sulphide ores.

130 Footnote 8, p. 649.

131 Emmons, W. H., Principles of Economic Geology, 2nd Edition, 1940, p. 181.

132 Wandke, A., and Moore, T. G., Pyrometasomatic vein deposits at Tepezala, Mexico. Econ. Geol. 30: 775, 1935.

133 Footnote 6, pp. 516–517.

134 Chapman, E. P., Newly recognized features of mineral paragenesis at Leadville, Colorado. Trans. A.I.M.E. 144: 265, 1941.

Spurr [135] says that the nature of iron minerals in an ore suggests a good deal as to the pressure, and thus as to the depth of formation—oxides, sulphides, and carbonates indicate successive stages of time and probably falling temperatures and reduced pressures.

Lindgren [136] gives in considerable detail the kinds of carbonate associated with well known ore deposits, and their classification in thermal zones. Beyschlag, Vogt and Krusch [137] suggest that in a considerable number of veins calcite dominates the upper part of veins in which quartz dominates below. Langford [138] reports that some important Canadian gold ores are associated with ankerite, whereas the veins of an outer zone with calcite gangue, are barren.

Naturally, other minerals associated with the carbonates are very helpful in estimating the temperatures and depths of formation of the carbonates. There are, as epithermal examples, the chalcedony-cinnabar veins with calcite (Fig. 87), and the Oatman, Arizona, adularia-gold ore replacing calcite (Fig. 70); as a mesothermal example, the Butte copper ores with rhodochrosite (Fig. 60); and as hypothermal examples, the garnet-actinolite-pyrrhotite copper ores of Ducktown, Tennessee (Fig. 80) and the ankerite-tourmaline-specularite gold ores of Ontario (Fig. 68). Others are too numerous to mention.

Some mineral combinations may leave doubt as to the thermal zone of their origin. There are veins cutting the Cuyuna ores (Fig. 32) where the acmite and manganiferous carbonate suggest a higher temperature than the later central adularia in the same vein.

The structures and textures of the several thermal zones are summarized by Lindgren,[139] and by Emmons.[140] The epithermal deposits are more drusy, brecciated, delicately banded (often symmetrically), crustified, and show colloform and cockade structures, and quartz blades related to carbonate cleavages. Schaller [141] gives a careful description and discussion of such quartz blades. From the present study of carbonates the following microscopic features might be added as suggestive of epithermal origin—a variability of size and habit of the carbonate, a relatively strong dustiness of the carbonate, more zoning and curvature during growth, and more flamboyant structure than is common in hypothermal carbonate.

The hypothermal carbonates are more massive, have perhaps more comb structure, more sutured intergrowths, more bending and granulation by deformation; it may be added that possibly a more extensive study would show that hypothermal carbonate grains have more liquid and gas inclusions, and the bubbles in the inclusions are relatively large. The hypothermal veins all have more tendency to replace their walls than the epithermal. An instructive

135 Footnote 11, p. 52.

136 Footnote 43, pp. 486–745.

137 Beyschlag, F., Vogt, J. H. L., and Krusch, P., The Deposits of useful Minerals and Rocks. Translated by S. J. Truscott, 1914, p. 211.

138 Langford, G. B., Geology of the McIntyre mine. A.I.M.M.E. Tech. Paper 903, 1938.

139 Footnote 43, pp. 190–209.

140 Footnote 131, pp. 50–81.

141 Schaller, W. T., The crystal cavities of the New Jersey zoolite region. U. S. Geol. Survey, Bull. 832, 1932, pp. 46–50.

slide is one from Michigan showing metallic copper along a zone in a transparent calcite (Fig. 81); the inner zone shows large rhombohedral cavities (negative crystals) with gas bubbles in a liquid; none were found in the zone outside the copper grains. This might suggest that the inner zone is mesothermal and the outer zone epithermal.

Mesothermal veins are intermediate, though the preceding notes contrast two extremes of temperatures. Possibly the intermediate temperatures and pressures are optimum for certain structures such as pseudomorphs, and for coarse milky quartz.

Most of the features noted are only suggestive rather than strictly diagnostic. There are many exceptions, gradations, and conflicting evidences.

Walker and Parsons [142] report that high temperature calcite may be distinguished from low by these features;—a pearly luster, an optic angle of about 15°, no complete extinction, and an unusually flat rhombohedral cleavage. At the other extreme, cold water calcite is probably best represented by the simple white sugary filling of joints in limestone (Figs. 50, 82).

[142] Walker, T. L., and Parsons, A. L., The characteristics of primary calcite. Univ. of Toronto Studies 20: 14–17, 1925.

ARTIFICIAL RECHARGE OF GROUND WATER ON LONG ISLAND, NEW YORK.

M. L. BRASHEARS, JR.*

ABSTRACT.

In 1933, the water table in a large area in western Long Island was below sea level, and potability of ground water was threatened by inflow of sea water. To prevent further overdevelopment, the New York State Water Power and Control Commission has required that water pumped from new wells for cooling and similar purposes be returned to the ground. During the summer of 1944, over 200 recharge wells and several recharge pits were returning water at the combined rate of about 60,000,000 gallons a day. Also in operation were several large recharge pits which return storm sewer runoff in Nassau County. The water is returned to glacial beds from which most of it is pumped, but in places it percolates into the underlying Cretaceous formations. Well drillers have developed recharge wells capable of returning as much as 1,000 gallons a minute, many of them having been in operation for over 5 years without failing. Recharge pits dug in coarse glacial gravels are capable of returning about 1,000,000 gallons a day per acre of exposed surface. The legal requirement that water pumped for cooling be returned to the aquifer has caused a gradual decrease in net withdrawal of ground water but has increased actual use. Hence a rise in water levels has occurred in the critically overdeveloped area. Water levels reached lowest stage at the end of 1941 and have recovered slowly since then. However, water levels are still far below sea level in many places, and sea water continues to move inland in areas of heavy pumping.

INTRODUCTION.

BECAUSE of the wide-spread occurrence of highly productive water-bearing material and other favorable factors, the ground water resources of Long Island have been used extensively for many years for industrial and public water supplies. Overdevelopment in the heavily industrialized and populated area at the western end of the Island caused a gradual decline of water levels and in 1933 it was discovered that the water table was below sea level in an area of more than 40 square miles and that sea water was moving into this area. The State Legislature, recognizing the seriousness of the situation, took steps to protect the public water supplies on Long Island from further overdevelopment and passed a conservation law requiring that the approval of the State Water Power and Control Commission be obtained before constructing a well having a capacity of greater than 100,000 gallons a day. In general, it has been the policy of the Commission, since the passage of the law, to require water pumped from new cooling and air-conditioning wells to be returned to the aquifer from which it is withdrawn. Since the passage of the law many new supply wells for cooling and air-conditioning have been drilled and because of the requirement of the Water Power and Control Commission

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a number of large recharge basins and more than 200 recharge wells, many of which have been in operation for over five years without failing, have been installed to return their discharge to the ground. During the summer of 1944, these recharge wells and basins were operated at a combined rate estimated to be more than 60,000,000 gallons a day which represents an average ground water withdrawal for an entire year of from 15 to 20 million gallons a day. Thus, the conservation policy of the Commission has permitted the drilling of a large number of new supply wells for industrial cooling and comfort air-conditioning but at the same time has prevented further substantial overdevelopment.

Because of its relatively low temperature during the summer months ground water is used for cooling and air-conditioning by many establishments on Long Island—theatres, restaurants, ice plants, public buildings, breweries, and manufacturing plants—having in most cases peak daily requirements of from 500 to 1,000 gallons per minute, but with some of the larger plants having daily requirements of as much as 5,000 gallons per minute. Most of the cooling plants are situated in Kings (Brooklyn) and Queens Counties (Fig. 1), and because only limited space is available in these urban areas at the western end of the Island, only recharge wells have been used to return cooling water. In contrast, recharge basins have been installed at several of the larger installations—mainly air-conditioned war plants—situated in the rural areas in Nassau and Suffolk Counties. Recharge wells having capacities of as much as 1,000 gallons per minute have been successfully constructed and as the demand at most plants is usually less than this limit, most of the cooling installations have required only one recharge well. However, at some of the smaller plants, because of unfavorable geologic and ground-water conditions, it has been necessary to construct more than one recharge well to return the discharge from only one supply well. At the larger plants, either recharge basins—capable of returning three to four million gallons a day—or several recharge wells have been utilized to return cooling water.

Depending upon the type of cooling plant, the temperature of the water returned to the ground ranges from about 2 to 20 degrees higher than the temperature of the water pumped from the ground. As shown by Leggette [1] and the writer [2] the return of warm water causes a rise in ground temperature. In some places this rise has been substantial and has decreased the advantage of using ground water for cooling purposes by causing a decrease in plant efficiency and an increase in operating costs. However, appreciable areal rises of ground water temperature have occurred only in the vicinity of centers of considerable recharge. Where wells are not closely spaced or are separated by impervious layers there has been no serious rise in the temperature of the ground water.

In addition to the return of warm water from cooling and air-conditioning plants, and occasionally from dewatering wells used during sub-surface con-

[1] Leggette, R. M., and Brashears, M. L., Jr.: Ground water for air conditioning on Long Island, New York. Am. Geophys. Union Trans., Part I, pp. 415–417, 1938.

[2] Brashears, M. L., Jr.: Ground water temperature on Long Island, New York. Econ. Geol., 26: 821–828, 1941.

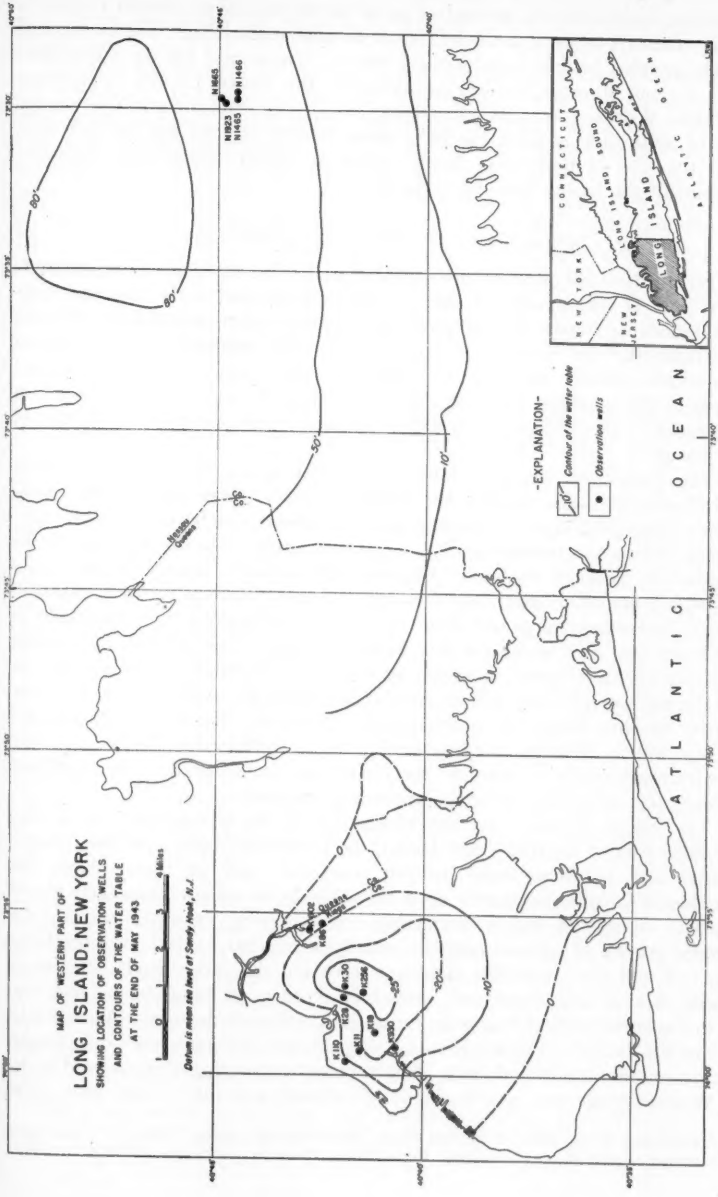

FIG. 1. Map of western part of Long Island, N. Y., showing location of observation wells and contours of the water table at the end of May 1943.

struction, a considerable amount of storm sewer run-off in Nassau County is being returned to the ground by means of water spreading. Eleven seepage basins, ranging in area from about 1 acre to 9 acres and having a combined area of about 40 acres, are being operated by the Nassau County Department of Public Works. According to reports based on general records, the average rate of infiltration in these basins is about 500,000 gallons per day per acre, with the rate of infiltration being somewhat higher immediately after the bottoms of the basins have been scarified.

GEOLOGY AND GROUND WATER CONDITIONS.

Long Island is composed of Coastal Plain sediments lying uncomformably on a floor of metamorphic rocks of pre-Cambrian and early Paleozoic age. The sediments consist of a considerable thickness of unconsolidated deposits of Cretaceous age overlain in most places by a relatively thin mantle of Pleistocene outwash and till.[3] The bedrock, which consists mainly of gneiss, slopes to the southeast at about 100 feet to the mile and crops out only in a small area in the northwestern part of Queens County, at the western end of the Island.

The Cretaceous deposits consist of a thick series of interbedded sands and clays which also slope to the southeast. The lower part of these sediments, considered to be of Raritan age, is composed chiefly of clay that overlies an extensive artesian aquifer, the Lloyd sand. The upper part of the Cretaceous, believed to be of Magothy age, consists largely of fine sand containing numerous relatively thin beds of clay. Several fairly widespread beds of water-bearing gravel occur in the beds of Magothy age, especially in the lower part just above the clay of Raritan age. The Cretaceous artesian beds are the chief source of supply of a number of Public Water supplies in the central part of Long Island, particularly along the shore lines and on the barrier beaches where the overlying glacial deposits can be readily invaded by sea water. Because they generally lie at considerable depths, and are relatively expensive to develop, the Cretaceous beds have not been utilized to any great extent for industrial or cooling purposes.

The glacial deposits rest unconformably on the Cretaceous. In a considerable part of western Long Island, the Cretaceous beds have been deeply eroded and in some areas entirely removed, and in these places the Pleistocene deposits lie directly upon the old bedrock surface. The early glacial deposits consist of highly permeable water-bearing outwash gravels—the Jameco gravel, an artesian aquifer—which are overlain by beds of interglacial clay, silt and fine sand—the Gardiners clay and the Jacob sand. The early glacial deposits are distributed around the borders of Long Island and also lie in the buried valleys that were cut in the Cretaceous deposits at the western end of the Island. The uppermost and youngest sediments on Long Island, except for minor accumulations of very recent material, are considered to be of Wisconsin age and consist chiefly of outwash and till. These beds cover

[3] Thompson, D. G., Wells, F. G., and Blank, H. R.: Recent geologic studies on Long Island with respect to ground water supplies. ECON. GEOL., 32: Figs. 1 and 2, p. 454, 1937.

most of the Island and the outwash is the chief source of ground water on Long Island.

Although the uppermost beds of outwash sand and gravel are interspersed with thin layers and lenses of clay and silt that confine the ground water at some places, ground water occurs chiefly under water table conditions in these beds. The lower beds, however, are covered almost everywhere by extensive overlapping and interfingering layers and lenses of clay and silt which confine the ground water. The glacial beds are more productive and the temperature of the ground water in them is normally lower than that in the Cretaceous deposits. Because of these factors, and also because they lie at shallower depths and can be more economically tapped, most of the ground water pumped for industrial and cooling purposes is withdrawn from the glacial outwash. Likewise, most of the warm water discharged from cooling plants is returned to these beds.

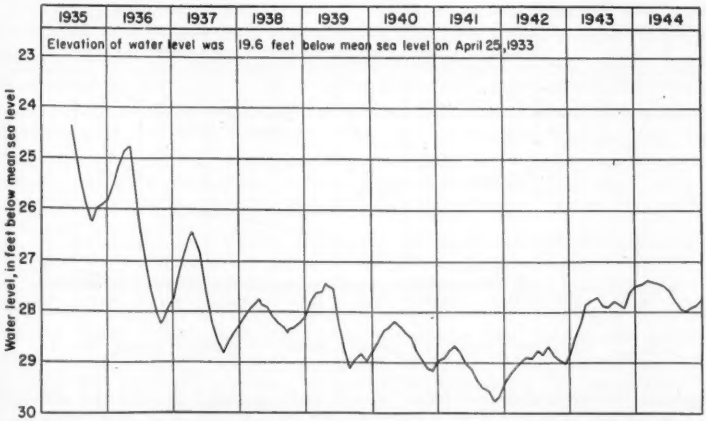

FIG. 2. Movement of water level well K-30, Kings County (Brooklyn), N. Y.

The overdevelopment of the ground water resources in the western part of the Island has caused the water table to decline considerably below sea level in most of Kings County and western Queens County and a "crater-like" depression has been formed on the water table. The area in which ground water levels lie below sea level is shown on Fig. 1, which also indicates that the bottom of the depressed area lies more than 25 feet below sea level.[4] The depth of the water table is also illustrated by the graph on Fig. 2, which shows the trend of water level since 1935 in an observation well, K-30, situ-

[4] For a more detailed statement and maps showing water levels, see Jacob, C. E.: The water table in the western and central parts of Long Island, New York State Water Power and Control Commission Bull. GW-12: 24 pp., 1945.

ated near the bottom of the "crater." [5] Elsewhere on Long Island, the water table, as shown by Fig. 1, generally slopes toward the shore and at places stands more than 80 feet above sea level.

As a result of the lowering of the water table in western Long Island, sea water from the surrounding tidal bays and estuaries has moved into the periphery of the "crater." The graphs on Fig. 3 show the chloride content

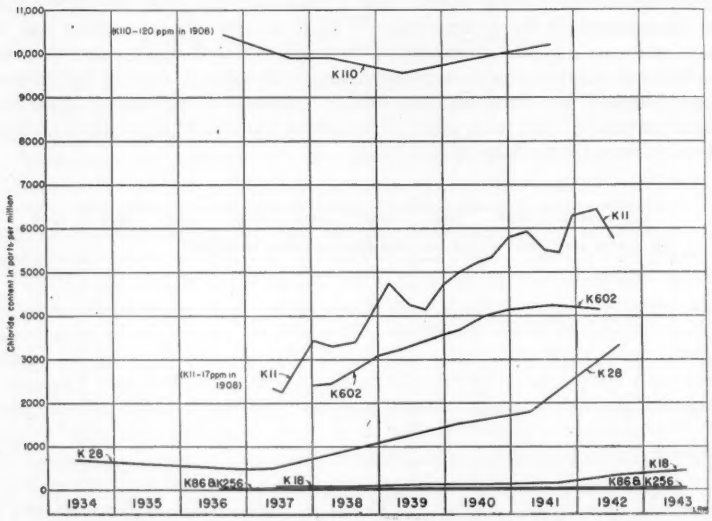

FIG. 3. Chloride content of ground water in Kings County, N. Y.

of ground water withdrawn from several wells situated around the northern part of the "crater" (Fig. 1). The chloride graphs for three sets of wells—K-110, K-11, K-18; K-28, K-256; and K-602, K-86—have been given in order to indicate the extent of the salt water encroachment and its rate of movement inland. The location of these wells, which are all used for cooling purposes, is shown on Fig. 1. Wells K-11, K-28, K-86, and K-602 are used throughout most of the year, whereas the other three wells are used chiefly during the summer cooling season. The features shown by the graphs are fairly typical of chloride conditions at other similar wells in the areas covered. The graphs for wells K-86 and K-256 indicate that the ground water in the central parts of the "crater" is relatively fresh and has not yet been invaded by salt water, whereas the graph for well K-110 shows that along the coastline the chloride content has become more or less stabilized at a high level. A single record, shown on Fig. 3, from an old well at the same plant as well

[5] For a more detailed statement of the trend of water level in well K-30, see Brashears, M. L.: U. S. Geol. Survey Water-Supply Paper 944, pp. 117–119, 1944.

K-110 indicates that encroachment had begun at this place as far back as 1908. A single record of the salinity of well K-11 in 1908 is also shown on Fig. 3. The chloride content at that time, 17 parts per million, in contrast to well K-110 in 1908, indicates fresh water conditions. Available records indicate that the chloride content of Upper New York Bay and the East River, although variable, is on the average about half that of sea water, or about 12,000 to 13,000 parts per million. It would appear, therefore, that the chloride content of the ground water in the area around well K-110 has reached and become stabilized at about the maximum possible salinity. Furthermore, it is apparent from the remainder of the graphs on Fig. 3—wells K-11, K-18, K-28, and K-602—that sea water has moved inland at a fairly rapid rate, during the past few years.

RECHARGE WELLS.

The operation of a recharge well is similar to that of a supply well except that the flow of water is in the opposite direction. When water is poured into a recharge well, the head in the well is increased. As a result, a cone of elevation is produced on the water table in the area surrounding the recharge well. The cone of elevation is similar to the cone of depression produced around a pumping well, except that the apex of the cone is above the water table. If a supply well and a recharge well are close together, as is the case at many installations on Long Island, some of the water discharged from the recharge well will be drawn into the supply well.

Various kinds of recharge wells have been constructed on Long Island but essentially all of them fall into two basic classes of construction, the so-called "dry type" and the so-called "wet type." The former consist of cased holes that end above the water table whereas the latter are screened below the water table. A few recharge wells have been constructed with the screen partially above and partially below the water table. Available records indicate that about 75 per cent of the recharge wells so far constructed are screened below the water table.

Each type of recharge well has certain inherent advantages not found in the other but, according to well drillers, the "wet type" of well is generally more successful. In the "dry type" of well, the warm water is usually discharged at a considerable distance above the water table permitting therefore some dissipation of heat as the water percolates downward to the water table. This type of recharge well is usually finished with a section of well casing into which slots have been cut whereas "wet type" wells are generally equipped with a standard well screen. Because of this factor and because they are shallower in depth, the "dry type" of well is less expensive to construct. However, excessive clogging is reported to take place in these wells because of the release of dissolved gases as the water leaves the discharge pipe and because the water comes in contact with oxygen in the air. Moreover, there are no adequate means of reconditioning these wells, whereas the same methods that are used to redevelop supply wells—surging, bailing, and acid treatment —can readily be applied to the "wet type" of well.

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The construction and successful operation of each recharge well is governed in large part by local geologic and ground water conditions. One limiting factor is the depth of the water table below the land surface. If the water table is shallow-lying, as is usually the case in seaside areas on Long Island, the permissible build-up of the hydrostatic head at the recharge well will be relatively small. In such areas, it is generally possible to create in a pumping well a drawdown of greater extent than the maximum build-up that can be attained in the companion recharge well. Thus, assuming equal conditions of well construction and equal permeabilities, the maximum possible rate of return may well be considerably lower than the rate of yield of the companion supply well. Under such conditions it is necessary to construct more than one recharge well to handle the discharge from a single supply well.

The presence of silt or other particles in the water discharged into a recharge well may clog the screen openings and may even pass through the screen and be deposited in the surrounding material, and thus reduce its permeability. Even though the amount of silt in the water is small, the aggregate may constitute a large quantity. For example, if the water pumped from a supply well on Long Island, which is operated about 1,000 hours during the cooling season at the rate of 500 gallons per minute, contained only one ounce of silt in every 100 gallons, it would carry nearly 10 tons of silt into the recharge well. It is very important, therefore, that a supply well be adequately developed to remove all sediment.

Because of the limited space available in the urban areas in western Long Island, it is frequently necessary to construct recharge wells within short distances of their companion supply wells. And since the Water Power and Control Commission requires that the warm water from cooling plants be returned to the aquifer from which it is withdrawn, it is of prime importance to secure the maximum possible vertical separation between the screens of the recharge well and the pumping well in order to take advantage of any impervious zones or other irregularities in stratification between the horizons at which the two wells are finished. If only a thin relatively impervious zone is present, the rise in temperature of the water pumped from the supply well would be much slower than if no such zone were present.

The data shown on Fig. 4 show the influence of irregularities of stratification on the rise of ground water temperature at a cooling plant in Kings County, New York, and indicate the desirability of utilizing favorable geologic conditions in constructing recharge and supply wells. At this locality (Fig. 1), glacial deposits containing three separate beds of sand and gravel rest directly upon the old bedrock surface. Two wells (K-930 and K-956), capable of pumping at a combined rate of over 1,000 gallons per minute, discharge into one recharge well, K-931. In the summer of 1939, one supply well (K-956) and the recharge well were both screened in the upper aquifer whereas the other supply well was pumping water from the middle bed of sand and gravel, which is separated from the upper horizon, as shown on Fig. 4, by a relatively impermeable zone. In 1940, both supply wells were deepened and thereafter tapped the lowermost aquifer which lies beneath a

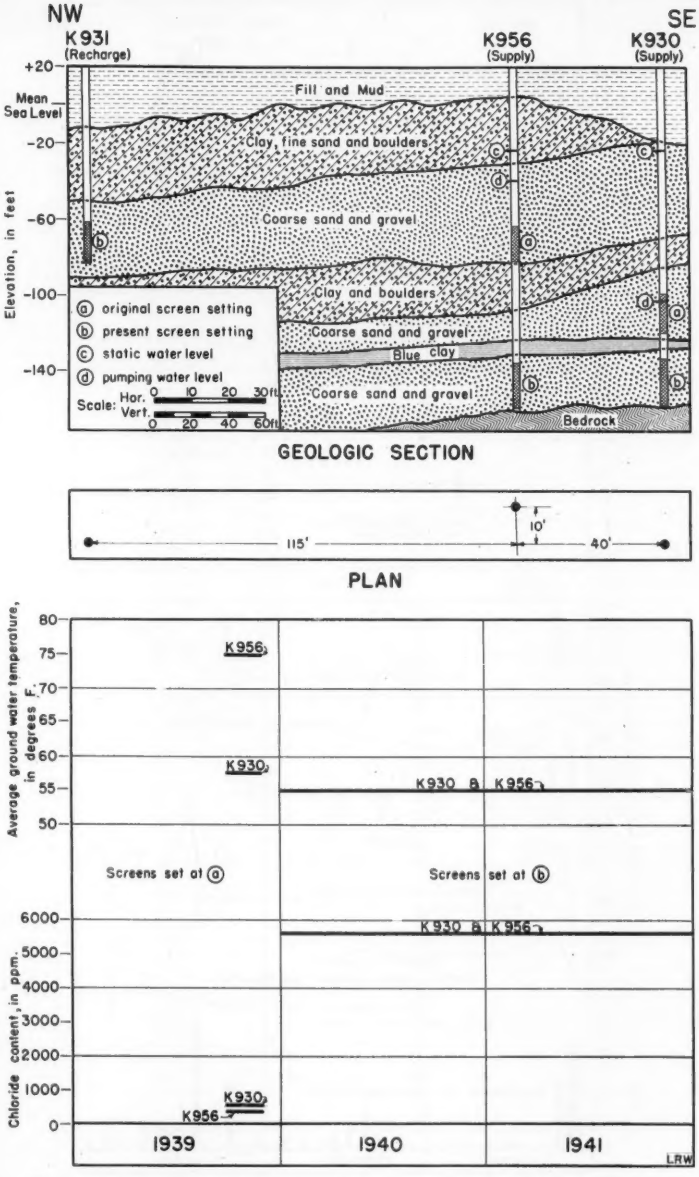

FIG. 4. Influence of geologic conditions on the fluctuation of temperature and salinity of water in wells in Kings County, N. Y.

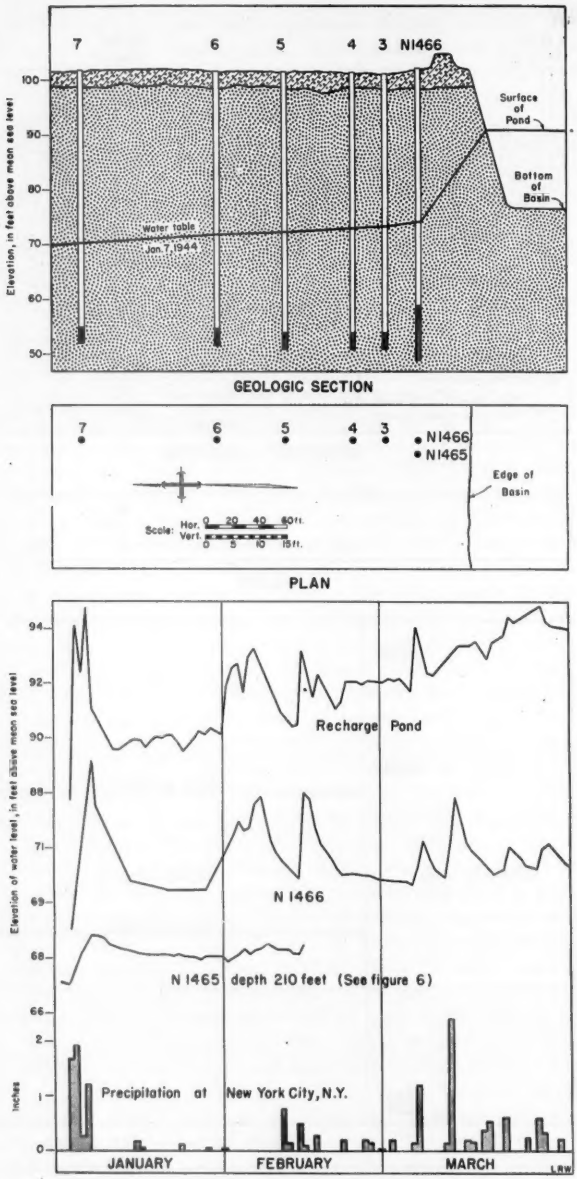

FIG. 5. Movement of ground water level in wells in Nassau County, N. Y., as result of recharge operations.

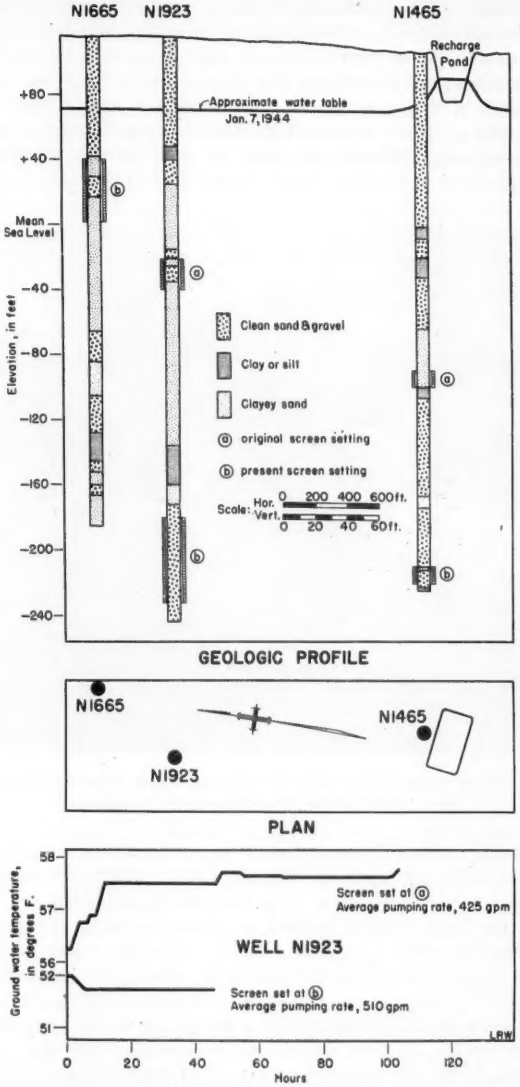

FIG. 6. Influence of geologic conditions on fluctuations of ground water temperature in wells in Nassau County.

thin layer of clay. The graphs of ground water temperature shown on Fig. 4 show the protective effect of the impermeable zones, and indicate that water pumped from the middle aquifer is only slightly affected by recharge in the upper zone and also that little if any warming occurs in the lower zone whereas the temperature of the water in the upper zone was raised about 20 degrees F. The graphs of chloride content for the two supply wells, also given on Fig. 4, by indicating differing salinities for each aquifer likewise show the hydraulic separation of the three beds of sand and gravel.

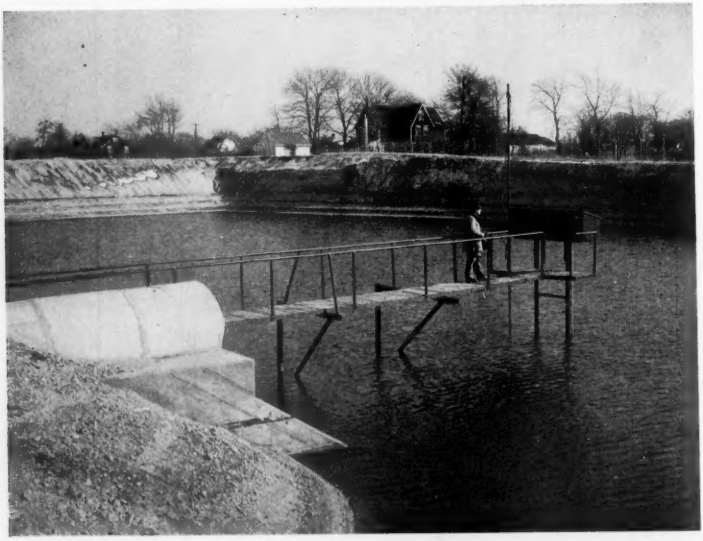

FIG. 7. View from northwest of recharge basin showing intake pipe and shelter housing water-stage recorder.

The protective effect of irregularities in stratification is again shown by the data for a large war plant in Nassau County where the water levels lie above sea level rather than below as is the case in Brooklyn. The recharge basin shown on Figs. 5 and 6 is used to return cooling water pumped from four large capacity wells (see also Fig. 1). Process water relatively high in impurities is also discharged into the basin which penetrates about 30 feet of coarse outwash and is about one acre in extent. The discharge into this basin ranges from about 300,000 gallons a day in the winter to about 3,000,000 gallons a day during the peak season in the summer. Previous to the construction of the basin, the warm water was returned by means of long, narrow trenches about 10 feet deep which were located in the vicinity of two of the pumping wells (N-1665 and N-1923). Warm water discharged from the trenches caused a rise of several degrees in well N-1665. Graphs giving the

fluctuation of water level in the recharge basin, a nearby shallow observation well, N-1466, and a nearby deep observation well, N-1465, are given on Fig. 5, along with a geologic cross section and the daily precipitation. The character of the deposits penetrated by well N-1465, which consist of Upper Cretaceous beds overlain by about 50 feet of glacial outwash, is given on Fig. 6, along with similar information for two other deep wells. A view of the recharge basin is given in Fig. 7, which also shows the location of the water-stage recorder operated on the basin.

The Cretaceous sediments are composed of alternating layers of sands and clays that vary considerably in thickness and extent and it is evident from the data on Fig. 6 that the extent of the lenses of clay is limited. The overlapping nature of the permeable beds and the absence of a widespread layer of clay provide the physical setting for vertical movement of water. And as might be expected, the graphs of water level on Fig. 5 confirm the geologic evidence that all of the permeable beds are hydraulically interconnected by showing that a rise in water level in the recharge basin causes a rise of water level in the deep well, N-1465, even though its screen lies below lenses of clay and beds of clayey sand. However, the hydraulic channels through the intervening lenses of clay are tortuous and cause a roundabout vertical movement of water, thus providing a means for dissipating the heat in the warm water, a feature that is illustrated in Fig. 6.

During the drilling of well N-1923, a test screen was set in the well at a depth of about 160 feet. Later on another test screen was set at a depth of about 320 feet. As shown by the graphs of ground water temperature on Fig. 6, warm water from nearby sources entered well N-1923 at the time it was test pumped at the higher level whereas the bed of clay lying above the lower screen prevented an inflow of warm water. By utilizing these favorable geologic conditions it has been possible to recharge the deep-lying water-bearing beds without causing a rise in water temperature.

SUMMARY.

Although the conservation policy adopted in 1933 by the Water Power and Control Commission has permitted the drilling of new wells for cooling purposes, further overdevelopment has been essentially prevented since water pumped from all new wells, except a few having capacities less than 100,000 gallons per day (70 gallons per minute), is being returned to the ground. In addition, a number of large wells drilled previous to 1933, which discharged cooling water to the sewers, have been abandoned since adoption of the conservation policy. Discontinuance of pumping at such wells thus has reduced to some extent the areal overdevelopment. Although water levels in the "crater area" continued to drop at a decreasing rate for a number of years after the conservation policy was adopted, a reversal in the trend of water levels, resulting from the gradual decline in pumpage in the area, took place near the end of 1941. Since then, as shown by the graph (Fig. 2) of water level in an observation well (K-30) situated near the center of the depressed water table, water levels have gradually recovered. However, the water table near the center of the overdeveloped area was still more than

27 feet below sea level at the end of 1944 and the inflow of sea water has continued (Fig. 3). It is rather clear, however, that the conservation program of the New York State Water Power and Control Commission not only has prevented further overdevelopment but also has brought about a gradual overall improvement of conditions. As overall pumpage is further reduced, an additional recovery of water levels with a consequent reduction in rate of inflow of sea water is to be expected.

ACKNOWLEDGMENTS.

The ground water investigation which forms the basis of this paper is being conducted by the U. S. Geological Survey in cooperation with the New York Water Power and Control Commission, the Nassau County Department of Public Works, the Suffolk County Board of Supervisors and the Suffolk County Water Authority. Officials of these agencies, well drillers and well owners, furnished much information and assistance that has been helpful and the writer wishes to gratefully acknowledge their efforts in his behalf. The determination of the chloride content of well water was made at the Mount Prospect laboratory of the Department of Water Supply, Gas, and Electricity, City of New York.

THE ROLE OF SULPHUR BACTERIA IN THE FORMATION OF THE SO-CALLED SEDIMENTARY COPPER ORES AND PYRITIC ORE BODIES.

C. SCHOUTEN.

FOREWORD.

Pyrite and marcasite occur in many sedimentary beds and are common in slates, shales, mudstones or "foulbottoms." Syngenetic deposition of FeS_2 seems highly probable, provided that the sulphides are disseminated throughout these rocks. Sulphate-reducing, and hence H_2S-producing, bacteria may ultimately be responsible for the precipitation of the primary sulphides. Most investigators will be convinced of this mode of origin or at least will accept this possibility.

However it is not my intention to discuss this point here. I think pyrite and marcasite, if dispersed throughout the rocks mentioned above, may have been formed syngenetically with the sediments, and the precipitation of the iron sulphides may have been largely governed by H_2S produced by sulphate-reducing bacteria. Furthermore, I am convinced of the important changes, such as deformation, recrystallization and redeposition, which may result from different kinds of metamorphism. Diagenesis followed by intense metamorphism is likely to render such deposits almost unrecognizable.

The writer also believes that some copper and lead sulphides such as those in the Red Beds, and compounds of Va, U and other elements may be concentrated in sediments by descending solutions. Usually however these deposits are supposed to be epigenetic, since they exhibit widespread replacement. These occurrences are mainly limited to shallow waterbeds on the flanks of continental areas.

On the other hand, especially in German literature, some examples have been advanced of large and massive pyritic bodies, containing only minor gangue or country rock, and have been classified as sedimentary and syngenetic with the original material of the slates or shales.

Schneiderhöhn,[1] who is convinced of the syngetic origin of these pyritic ore bodies, and others have published some articles in support of this view. One of Schneiderhöhn's arguments in favor of a syngenetic origin is the existince in these deposits of very small sulphide spheres composed of tightly packed grains which he thinks originally were sulphur bacteria. In one article on the copper shale of Mansfeld Schneiderhöhn attempts to prove that the spheres are fossil organisms.

In an earlier publication[2] the present writer strongly opposed this point of view. It seems desirable now to advance additional evidence, especially since Schneiderhöhn's viewpoints appear to have gained ground in European literature, in order to show that the validity of his assertions is open to question. As I see it, his interpretation cannot be used as definite criteria against an epigenetic origin.

The following points of Schneiderhöhn's articles will be discussed: (1) Morphology of the sulphur bacteria; (2) Physiology and ecology of

[1] H. Schneiderhöhn, Neues Jahrb, f. Min. G. P., 1923, B. B. 47, p. 1. Metall und Erz, 1926.

[2] C. Schouten, Metasomatische Probleme, 1937.

these organisms; (3) Chemistry of the various deposits; (4) Ore genetics, especially respecting the copper shale.

On the first two points, reliance must be placed on data from the literature about recent forms of sulphur bacteria. The fourth point will be discussed in connection with my own ore microscopic observations.

INTRODUCTION.

THERE exists still much diversity of opinion and confusion as to the classification of the organisms, sometimes summarized under the name of sulphur bacteria. Hence, it is imperative to define properly the term "sulphur bacteria." The well-known and common sulphate-reducing bacteria, such as *Microspira,* which produce hydrogen sulphide from sulphates, should not be included in the group of true sulphur bacteria, also called *"Thiobacteria."* The latter can, according to Bavendamm,[3] be subdivided into the following groups:

(1) Those that do not store sulphur granules inside their cells
  (*a*) thiosulphate bacteria that oxidize thiosulphates
  (*b*) denitrifying bacteria that oxidize sulphur or thiosulphates by using oxygen derived from nitrates

(2) Those that store sulphur globules within their cells, viz.: the sulphur bacteria in the more restricted sense
  (*a*) colorless or *Leuco-thiobacteria*
  (*b*) purple or *Rhodo-thiobacteria.*

The organisms referred to by Schneiderhöhn are the spherical sulphur bacteria containing sulphur globules within their cells. This is undoubtedly clear from his description and from the fact that he calls attention to *Thiophysa volutans* and *Monas Mülleri* as two examples.

On the other hand it must be pointed out that, in addition to the true sulphur bacteria, the sulphate-reducing bacteria would also have played an important role. But, as this last point is admitted and not under discussion, we have to deal only with the *Leuco-* and *Rhodo-thiobacteria.*

MORPHOLOGY OF THE SULPHUR BACTERIA.

Description.—Schneiderhöhn in his treatise on the copper shale[4] considers the small sulphide spheres in this ore, composed of tightly packed grains of chalcopyrite, to be fossil sulphur bacteria. The separate sulphide grains together building up a sphere as a whole would then represent the sulphur granules originally stored inside the cells of living organisms. These sulphur globules during the ore-forming process were presumed to have been converted into the sulphur-rich copper compound, chalcopyrite. Schneiderhöhn stated that the forms, structures and order of dimensions of these sulphide bodies agree with those of the most common recent types of sulphur bacteria. Hence, in the fossil state each single spherical sulphide aggregate would rep-

[3] W. Bavendamm, Die farblosen und roten Schwefelbakterien.
[4] Neues Jahrb. f. Min., 1923, B. B. 47, p. 1.

resent a sulphur bacterium, each simple chalcopyrite grain of the sulphide sphere would originally have been a granule of elementary and intracellular sulphur. Although Schneiderhöhn in his comparison mentioned only the well-known recent forms, it seems advisable to include also species hitherto unknown.

Equality or differences in dimensions will seldom be convincing to prove the existence or absence of these fossil organisms. Therefore, considering the morphology of these bacteria, the dimensions, form and internal structure will be distinguished. As the sulphur bacteria show great variety in form, internal structure, and different phases of development, morphology in its entirety may become strong evidence against Schneiderhöhn's theory, especially if the other confirmatory evidence against his theory, which will be discussed in other parts of this article, is also taken into account.

Schneiderhöhn in 1923 divided the sulphide units under discussion into four groups as follows:

(1) Spherical or bar-like bodies of .004 to .008 mm diameter on an average, and up to .02 mm long, composed of tightly packed and equi-dimensional points of chalcopyrite. Generally no groundmass is detectable. In some of them, if the points are not too crowded, chalcocite could be determined as interstitial material.

(2) Spherical, elliptical or constricted forms of the same order of magnitude as under (1) but composed only of bornite or chalcocite without indication of an internal structure. On the other hand, the .004–.006 mm spheres, consisting merely of bornite or chalcocite, do not show transitions to larger bodies of the same form. They are characterized by the spherical form, whereas larger and concretional lenses of ore are always elongated and more or less pointed.

(3) Somewhat larger bodies measuring up to .015 mm diameter, generally spherical, and composed internally, as those of group 2 of bornite or chalcocite, but bordered by a few points of chalcopyrite. In the main they consist of bornite or chalcocite, the outer rim however being occupied by extremely small chalcopyrite grains, or the interiors contain few points of chalcopyrite.[5] Other forms occur as spheres of the same diameter, but the small chalcopyrite grains are larger and more heaped up, and clearly triangular in section.

(4) The bituminous matter is spangled with dust of innumerable extremely small and hardly determinable chalcopyrite points.

In 1926 Schneiderhöhn stated: "As nobody denies the important role of bacteria in the sulphur cycle during the formation of sapropel, every doubt as to these bodies being essentially mineralized sulphur bacteria is unjustified in view of the formal similarity."

This raises the question: Which sulphur bacteria are to be considered?

In the first place, as stated above, only the spherical forms of .004 to .008 mm diameter, consisting of tightly packed chalcopyrite points, have to be examined.

[5] Elsewhere in the same article he says: "These forms frankly may be considered as bacteria on the verge of starvation."

Among the spherical *Rhodo-thiobacteria* only *Thioporphyra volutans,* a recent species described by Ellis in 1926 with an average thickness of the cells of .007 mm, ought to be considered and will be discussed further on. All other recent *Rhodo-thiobacteria* without exception may be excluded as being too small, as they show dimensions of .001–.005 mm, mostly ranging only from .001–.003 mm. Furthermore, all representatives of *Chromatiaceae,* another group of the *Rhodo-thiobacteria,* are impossible since they are all ovoid, elliptical, or cylindrical. Consequently, none of the colored or purple recent sulphur bacteria, except the *Thioporphyra volutans,* ought to be considered.

The group of *Leuco-thiobacteria,* or colorless sulphur bacteria, remains to be discussed. Some of these show thread- or spiral-forms, others egg- or bean-shaped forms with the sulphur drops generally concentrated at one of the poles; still others assume heart-form in division. *Hillhousia mirabilis,* described by West and Griffith, is a giant bacterium of too large dimensions to be considered. Hence, all these species are highly improbable. The only three recent species of the *Leuco-thiobacteria* left as comparable with the supposed fossil forms are: *Thiophysa volutans* (described by Hinze), *Thiovulum Mülleri* or *Monas Mülleri* (described by Warming and Lauterborn), both mentioned by Schneiderhöhn, and *Thiosphaerella amylifera* (described by Nadson).

The following remarks may be made about the morphology of these species:

Thiophysa volutans has one globular or ovoid cell, bordered by a thin double membrane; its diameter ranges from .007 to .018 mm, the maximum dimensions being .029 mm long and .018 mm wide. Uni- and diplo-cocci are common. In normal circumstances the bacterium is more or less filled with sulphur globules, serving as reserve food; generally the sulphur is irregularly distributed within the cell. In 24 hours in pure water these sulphur globules grow smaller and decrease in number or disappear completely. While division is in progress, the sphere transforms to an ellipse, then the coccus becomes constricted, and two flattened cells, frequently of cap-form, are the final result.

Monas Mülleri is .006–.013 mm in length and .005–.010 mm in width, hence is ellipsoidal to globular, but sometimes this bacterium is pointed or considerably flattened. The sulphur granules are generally concentrated at the thicker end of the cells, and in division the bacterium assumes a heart-like form.

Thiosphaerella amylifera (Nadson) has spherical or ellipsoidal cells .006 mm long and .005 mm wide. Reproduction is by fission. Preparatory to division the cell is constricted in the middle.

There finally remains to be considered the only possible recent representative of the *Rhodo-thiobacteria* mentioned above:

Thioporphyra volutans. Cells are spherical or ovoid with an average diameter of .007 mm. Uni-coccus as well as diplo-coccus and more seldom tri-coccus, with the three units arranged in triangular formation or in linear arrangement, are known. While division is in progress, the sphere elongates slightly, then the coccus becomes constricted in the middle. Sometimes after

constriction the division does not take place and the cell takes the shape of a diplo-coccus. Division may also be by budding.

The sulphur drops may completely fill the cell or they may be few in number or even absent. In ovoid cells the sulphur may be concentrated at one end.

This purple sulphur bacterium, the only one of the recent *Rhodo-thiobacteria* whose dimensions are comparable with the sulphide spheres under discussion, was not described until after the publication of Schneiderhöhn's article.

Having given the most important morphological properties of the known recent sulphur bacteria, it seems advisable to enter into some particulars about other ore-deposits.

Schneiderhöhn refers to Meggen and Rammelsberg as two other pyritic deposits where these fossil-bacteria would be abundant. In Rammelsberg however the diameter of the pyrite spheres is about .015 mm and in Meggen .010 up to .030 mm. In the so-called "Dachklotz"—the Zechstein-limestone directly overlying the copper shale—essentially the same spheres occur, but ranging from .040–.080 mm, thus, of dimensions comparable with those of the giant bacterium *Hillhousia mirabilis,* which, however, has rounder cylindrical forms of about .026 mm in width and .060 mm in length.

No recent sulphur bacteria of spherical form are known answering all these fossil-dimensions.

In addition, it must be remembered that the normal pyrite spheres in all these deposits are built up of tightly packed pyrite or chalcopyrite grains; sulphide-globules composed of loosely packed grains or spheres in which these sulphide grains are unevenly distributed are absent or relatively rare. In the latter case, as will be shown later, another "replacing" sulphide comes into play. Often the sulphide grains composing a sphere are so crowded that in polished surfaces the separate grains are not distinguishable and become visible only after etching (Fig. 89).

This does not correspond with the normal distribution of the sulphur granules in most of the sulphur bacteria and surely not of "bacteria on the verge of starvation." In this respect it may also be emphasized that the ores of Rio Tinto in Spain, still considered by Schneiderhöhn in 1944 as of hydrothermal origin, are rich in analogous pyrite spheres (Fig. 87). The writer even discovered such spheres in a pyrite-marcasite mass from the tin veins of Cornwall (Figs. 88, 90).

Conclusion.—Thiophysa volutans, Monas Mülleri, Thiosphaerella amylifera as representatives of the *Leuco-thiobacteria* and *Thioporphyra volutans* of the *Rhodo-thiobacteria* are the only well-known recent species whose diameters are comparable with the sulphide spheres of the copper shale. Taking into account the deposits of Meggen, Rammelsberg and the "Dachklotz," overlying the copper shale, no recent sulphur bacteria of the globular form are known to compare with these presumably "fossil" forms.

The supposition could be made, that spherical sulphur bacteria of the desired size might have lived in past geologic periods. But even then the existence of fossil sulphur bacteria—considering also the dimensions, forms,

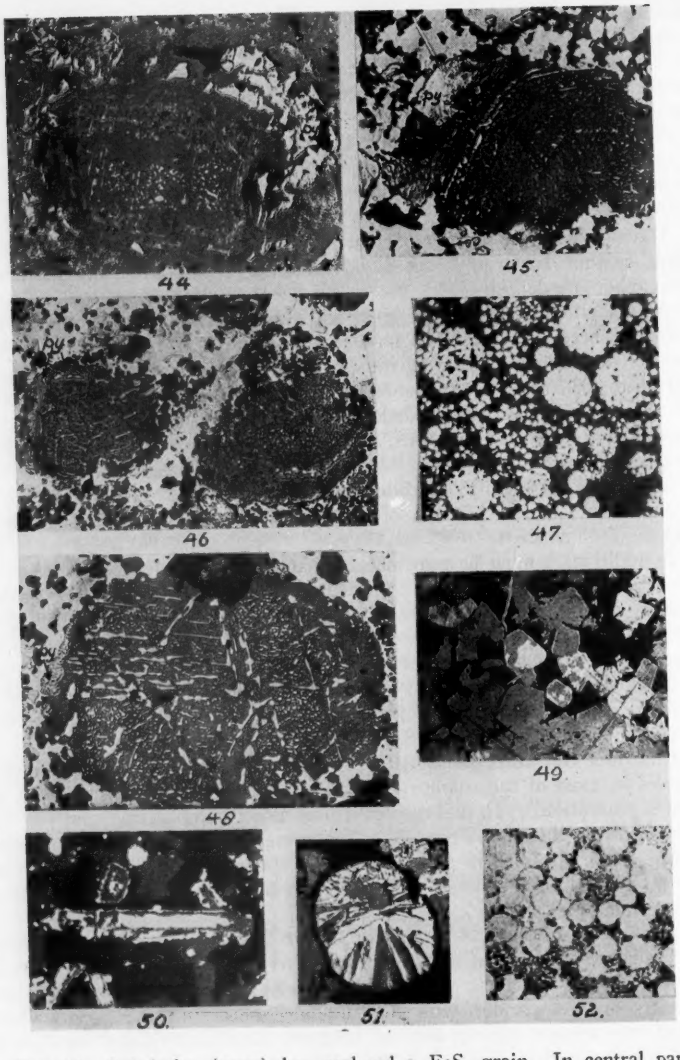

FIG. 44. Sphalerite (gray) has replaced a FeS_2 grain. In central part of sphalerite body are fine inclusions of chalcopyrite (white) surrounded by a zone of small pyrrhotite blebs. Further outward, pyrite remnants (larger white fragments) are zonally arranged more or less indicating the outermost zone of the original pyrite grain. Black, pits in surface. × 200. Rammelsberg, Germany.

FIG. 45. Fragment of FeS_2 crystal (pyrite?) almost completely replaced by

and internal structures—seems highly improbable. For sulphur bacteria show a great variety in form, internal structure and in different phases of development, properties which ought to be found in fossil forms. This, however, is not the case, although the author paid much attention to this point during the microscopic investigations. The following differences between sulphur bacteria and the so-called fossil forms apply to recent species as well as to species hitherto unknown.

(1) In division the cells are mostly elongated. The sulphide bodies in question are almost always spherical or perhaps a little irregular; ovoids or ellipses comparable with elongated cells of the living organisms were seldom found (see Figs. 47, 85, 89, 90, 52).

(2) In division the cells are constricted or may show buds. The sulphide spheres never show forms characteristic of such a constriction. Rarely, two sulphide spheres that happen to touch each other may resemble somewhat such constricted forms, but are probably formed quite differently.

(3) The cap-forms commonly assumed by the sulphur bacteria just after division were never observed in mineralized form.

(4) Transitional forms, where the sulphide specks in the interior of the sulphide spheres are less tightly or loosely packed, or where these are almost missing, could not be discerned, at least not in the case of a single sulphide. Schneiderhöhn reported, it is true, spheres with only a few chalcopyrite points in the center, but then the groundmass consists of another sulphide, such as bornite or chalcocite. These will be discussed under the heading of "Ore genetics."

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sphalerite (dark gray) with many inclusions of chalcopyrite (fine white blebs) in groundmass consisting of intergrowth of sphalerite and chalcopyrite. Py are pyrite remnants. Chalcopyrite inclusions in sphalerite and pyrite remnants are zonally arranged and are parallel with outline of original FeS_2 crystal. × 500. Rammelsberg, Germany.

FIG. 46. Two FeS_2 concretions replaced by sphalerite (dark gray) with fine chalcopyrite-pyrrhotite inclusions (white) in groundmass of chalcopyrite, galena and pyrrhotite (all three white) with some gangue (black). Some fine pyrite remnants (small white inclusions with relief along borders of sphalerite bodies). × 100. Rammelsberg, Germany.

FIG. 47. Spheres of pyrite (white) composed of tightly packed small pyrite crystals and loose pyrite crystals in matrix of sphalerite (gray). × 500. Meggen, Germany.

FIG. 48. Same as Figs. 44, 45 and 46. Blebs and laths of pyrrhotite (white) inclusions in sphalerite (dark gray) which is pseudomorphic after an original FeS_2 concretion in groundmass of galena and chalcopyrite (both white) with some sphalerite. Some fine pyrite remnants at the outline of the sphalerite body (near left border). × 200. Rammelsberg, Germany.

FIG. 49. Bornite (gray) and chalcocite (almost white) both pseudomorphic after pyrite crystals. Black, shale. Copper shale. Mansfield, Germany. × 400.

FIG. 50. Special zones from marcasite crystal (white) replaced by sphalerite (gray). Black, shale. Outlines and kernels are replaced with difficulty. Rammelsberg, Germany. × 500.

FIG. 51. Bornite (gray) has replaced certain zones from a radiated pyrite concretion (white). Two small FeS_2 spheres originally enclosed in the pyrite concretion have been replaced. Copper shale. Germany. × 800.

FIG. 52. Group of chalcocite spheres pseudomorphic FeS_2 spheres. Copper shale. Germany. × 800.

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(5) Specks of a single sulphide that build up to a sphere are always distributed regularly and heaped up in the same way, whereas in several species of the sulphur bacteria the sulphur globules are commonly irregularly distributed or concentrated at one pole.

Summarizing these morphological differences it can be stated that the morphological similarity of recent and even of unknown sulphur bacteria with the supposed fossil forms in the copper shale, strongly stressed by Schneiderhöhn, fails in many respects or at least is not proved. In any case the scanty data available are insufficient to exclude other possible modes of formation. Consequently, from this point of view the syyngenetic origin of the copper sulphides can by no means be considered as proved by these supposedly mineralized sulphur bacteria.

PHYSIOLOGY AND ECOLOGY OF THE SULPHUR BACTERIA.

The enormous accumulations of purple sulphur bacteria that now and then appear in bays have stimulated research work on this group, and their form and vital conditions are fairly well known. On the other hand, reliable data as to the complicated nature of the physiology of the *Leuco-thiobacteria* and the conditions essential for development on a large scale, in which we are especially interested, are relatively scarce. Investigators do not agree on many points and sufficient knowledge is lacking. It therefore seems astonishing that Schneiderhöhn used much unreliable data to prove the probability of their existence in the copper shale sea.

Some arguments derived from the physiology and ecology of the sulphur bacteria, which contradict the theory of Schneiderhöhn, are:

(1) The complicated nature of the physiology of the sulphur bacteria requires an extremely fine adjustment and it seems doubtful whether the combination of all these highly specific requirements has been fulfilled in the copper shale sea.

(2) The existence of fossil sulphur bacteria in ore deposits of such variable sulphide content as well as such variable composition of the bordering and underlying country rock (e.g., Mansfeld, Meggen and Rammelsberg) seems improbable.

(3) Comparison with the Black Sea does not appear justified.

(4) The composition of the copper shale sea water, with its poisonous metal salts, would be a rather unfavorable medium for the full development of these bacteria.

(5) The sulphides are very irregularly distributed in the sediments, vertically as well as horizontally.

These arguments will now be considered in some detail.

With reference to (1), as already stated, the conditions that favor great multiplication of the sulphur bacteria in question are not well known. It is hardly possible to select the best growth conditions and still much more difficult to prove that the sea of a given geologic period is exceptionally favorable to their conditions of life, as Schneiderhöhn attempts to do. The quantity of plant remains on the bottom and on the surface of the sea; the fish

cadavers; the depth of the sea; the salt content of the water; the quantity of light; the relations between hydrogen sulphide, oxygen, metal salts and lime; the water currents and so on, may all be of the greatest importance for a marked increase in reproductive activity of these bacteria.

According to the literature, the colorless sulphur bacteria need H_2S and a certain minimum of oxygen as the bases for their metabolism. The H_2S taken up will primarily react with oxygen to produce sulphur which is stored in the cells. Then, in a second phase, the sulphur is oxidized to sulphuric acid. For proliferation of the bacteria the presence of carbonates would be essential for the neutralization of the acid formed.

Accepting that these organisms require a definite quantity of H_2S, a low maximum of oxygen and a certain quantity of $CaCO_3$, the existence of favorable conditions in this respect in the copper shale sea is not at all proved, although Schneiderhöhn tries to make it acceptable by arbitrary selection of the conditions. His statement that a sharp separation between the living area of sulphate-reducing and true sulphur bacteria need not necessarily be present, is apparently confirmed by the investigations of the life of these organisms. His further definite statement, however, that this separation was really present in the copper shale, but did not exist during the formation of the pyrite bodies of Meggen and Rammelsberg, is no more than an assertion to account for the differences in content and structure of these deposits.

The voluminous literature on the peculiarities of the copper shale sea permits one to select all data most suitable to one's theory; on equally consistent grounds one may arrive at the reverse conclusion.

Schneiderhöhn considers the shale in its initial stage as a foulbottom in which putrescible organic masses and sulphate-reducing bacteria produced H_2S, $(NH_4)_2CO_3$ and NH_4OH. The process of sulphide deposition then could start only after the liberation of H_2S had begun, in other words, after a fixed bed of plankton had been formed and was putrefying. This would be the reason why the first inch near the bottom of the copper shale is very poor in ore. But, after the deposition of a thin layer of putrescible plankton, the liberated H_2S in part would have precipitated the sulphides of the metal salts, in part it would rise in the water to a level where the sulphur bacteria could live. These bacteria falling down would be "tanned" directly in the copper-rich leaching solution at the bottom, whereas those which were still alive would be killed directly in the high H_2S concentration near the bottom. Against such a hypothetical cycle of events, the following statements and questions may be raised:

(*a*) The lowest layer of the copper shale is poor in ore, according to Schneiderhöhn, because of the absence of sufficient foulbottom beneath it. On the other hand, however, the upper inch of the footwall, known as the bleached arkose-sandstone "Weiszliegende," is in part rich in ore, which Schneiderhöhn considered to be primary, although no sapropel layer nor foulbottom existed in these underlying beds.

(*b*) How could the sulphur bacteria sinking from a higher level be "tanned" directly in a copper-rich solution at the bottom if the H_2S concentration there was high? This excess of copper and of H_2S would immediately

have resulted in precipitation of sulphides in preference to a reaction with the more resistant sulphur drops in the bacteria.

With regard to (2), in the Mansfeld copper shale the direct layer underlying the main ore body consists of coaly-marly-slate. In Meggen the thick footwall of the pyrite ore body is a sediment with the composition of a graywacke rich in quartz; the walls of the ore bed are extremely sharp and consist of extensive barite bodies. In Rammelsberg the enclosing rock is a Middle-Devonian slate rich in mica and poor in fossils. The so-called "Dachklotz," the limestone that forms the hanging wall of the copper shale series, should contain the largest growth of sulphur bacteria.

It appears unlikely that all these markedly different environmental conditions in divergent geologic periods, especially in Germany, were all very favorable to the life of the same types of sulphur bacteria.

Concerning (3), Schneiderhöhn compared the recent Black Sea, where the existence of a sulphur bacteria layer during a higher water level is generally accepted, with the copper shale sea and concluded that the copper shale showed the same separation of living area of H_2S-producing and sulphur bacteria. This comparison is unjustified.

In the "Limans" of the Black Sea the sulphur bacteria live, according to Jegunow, on or near the bottom. Where the depth of the sea exceeds 200 m they rise to a higher level. Perhaps a complete bacterial layer extends over the whole area of the sea up to the center, where the depth reaches more than 2,000 m. Andrussow is of the opinion that the Black Sea is especially favorable for their existence because vertical water currents beneath 170 m are absent.

Many investigators consider the copper shale sea as having been very shallow; some even declare that it dried up twice. The shale beds are very thin, they are absent or poorly developed at places where the bottom of the sea had low hills of only 5 to 10 m height. Small cliffs along the shores resisted destruction. This being admitted, it might be inferred that the depth and existence of the copper shale sea were entirely insufficient to justify a comparison with the Black Sea. A permanent bacterial level in the Mansfeld sea would then have been an impossibility. The presence of a continuous underlayer of saline water rich in H_2S—a realm of death for the sulphur bacteria—and a covering layer of fresh water rich in oxygen would be excluded.

It may be added that the true fossils found in the copper shale, the nature of the bottom mud or black shale, and the low pyrite and high siderite content are not in accordance with conditions prevailing today in the Black Sea.

Consequently, Schneiderhöhn's comparison of the Black Sea and copper shale sea conditions is not based on reliable grounds either palaeogeographically, bionomically or petrographically.

With reference to (4), Schneiderhöhn attempted to show that the low copper content in the sea water acted as a tonic to the life of bacteria. He emphasized Benecke's investigations with *Bacterium coli* which show the stimulating effect on the life of this bacterium of copper concentrations of 1 : 60,000 up to 1 : 50,000,000; a higher concentration would have a poisoning effect. He then calculated, on hypothetical grounds, that the copper content

of the sea lay exactly between these limits and concluded that they were specially favorable conditions of sea water.

A trace of copper in solution indeed favors the vital activity of *Bacterium coli*. It is highly questionable, however, whether it would be advantageous also to sulphur bacteria, because it would take away their H_2S food or eventually might react with the amorphous sulphur in their cells and cause their death.

Schneiderhöhn then assumes water currents rich in copper near the bottom and poor in copper in a higher level. This again, by the dilutions mentioned, and by the presumably small depth of the sea, seems puzzling.

The eventually poisoning effect of other metal salts such as lead, zinc, silver and arsenic is not dealt with by him. His attempt to make acceptable the favorable living conditions in this respect fails, and much more so if Meggen and Rammelsberg with their great pyrite-barite bodies almost free from accompanying gangue and country rock are taken into account.

With regard to (5), the physiology and ecology are not directly or clearly connected with the irregular distribution of the sulphides. This need not be considered here, but in 1944 Schneiderhöhn still considered the ore in the "Sanderz" (the bleached underlying "Red Beds") as primary and not infiltrated. This ore occurs well beneath the first sapropel layer and hence cannot satisfy the living conditions set forth by him.

CHEMISTRY OF THE VARIOUS DEPOSITS.

In 1923 Schneiderhöhn's opinion was that neither chalcopyrite nor pyrite was a part of the primary mineralization of the copper shale, and he even stated that he had never observed pyrite except in a few inclusions in ore lenses. He claimed in the same year that chalcocite was always pseudomorphic after bornite, and considered this replacement as a kind of autocementation. Furthermore, according to him, observations point to almost simultaneous deposition of the carbonates, calcite, dolomite and siderite, and of bornite. Chalcopyrite would be obviously secondary and younger as far as the main sulphide (bornite) is concerned.

More remarkable, however, is his statement that the chalcopyrite from the bacteria would be syngenetic and contemporaneous with the main sulphide bornite, as well as galena and sphalerite. In 1944 he adds that in shallower parts of the sea, zinc perhaps was first precipitated as carbonate, which was afterwards transformed to sulphide. He concluded: The copper sulphides in the copper shale are primary; they have been formed syngenetically in the lime-containing foulbottom as mixed iron-copper-sulphide gels under the prevailing influence of the bacteria of the sulphur cycle.

He then dealt at some length with the chemical equilibrium of CO_2, H_2S, $FeSO_4$ and $CuSO_4$ in order to explain the paragenesis of bornite and siderite, and the scarcity of pyrite. Taking into account only these minerals the simultaneous formation is not impossible.

However, in 1926, after Schloszmacher had stated that these supposed bacteria were mineralized pyrite (or marcasite) concretions, he confessed that pyrite occurred more commonly than formerly supposed and then claimed that

bornite and chalcocite were contemporaneous as well. Both bornite and chalcocite would have been formed as diagenetic crystallization from mixed copper-iron-sulphide gels.

However, the subject of equilibrium, brought forward as probable in 1923, was not touched upon in 1926. Finally in 1944, he mentions bornite, sphaler-

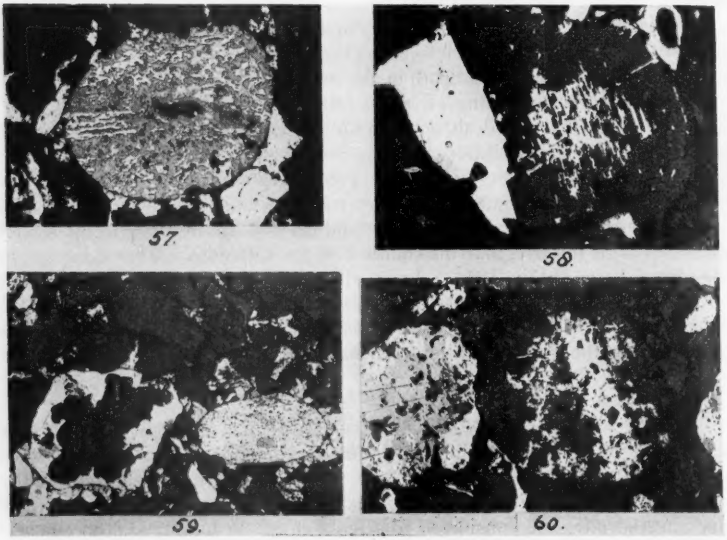

FIG. 57. Quartz or feldspar grain from the arkose sandstone completely replaced by sphalerite (gray), chalcocite (almost white) and some bornite (faint gray specks in chalcocite). Matrix black is arkose cement. "Weiszliegende" from copper shale. Germany. × 85.

FIG. 58. Same as Fig. 57. Partial replacement of a feldspar grain by galena (white). Same deposit as Fig. 57. × 85.

FIG. 59. Same as Figs. 57 and 58. Several grains (dark gray) of the arkose sandstone. One grain completely replaced by chalcocite (almost white) with some small bornite specks (pale grayish white). Another grain partly replaced by chalcocite. Some small sulphide specks in the cement. Same deposit as Fig. 57. × 50.

FIG. 60. Same as Figs. 57, 58 and 59. White, galena; faint gray, bornite; dark gray, grains of arkose sandstone. Same locality. × 90.

ite and chalcocite as the main sulphides, and pyrite, galena, tetrahedrite and native silver as less common, and thinks all these sulphides were precipitated as marine sediments. The growing impossibility of the equilibrium under these conditions was not discussed.

If pyrite, chalcopyrite (as mineralized bacteria), bornite, chalcocite and siderite, as according to Schneiderhöhn, were simultaneously deposited as

mixed gels, it would envisage the improbable supposition that compounds poorest in sulphur (siderite) and richest in sulphur (pyrite), and compounds poorest in copper (pyrite) and richest in copper (chalcocite), and also chalcopyrite and bornite would have been contemporaneous. This supposition seems fully untenable chemically as well as empirically. In ore genesis to date, these sulphides are always described as successive depositions of different ages, and a great body of observational data supports this point of view.

Hence, chemically as well, a syngenetic origin as mixed gels, as argued by Schneiderhöhn, is highly improbable. If it were true, the ore deposits of this copper shale would constitute the only known example in the world of such simultaneous deposition. These minerals can all exist side by side; the idea of their simultaneous deposition seems incompatible with the abundance of well authenticated observational data.

ORE GENETICS.

I admit that the arguments for a syngenetic deposition of FeS_2, with the aid of sulphate-reducing bacteria, dominate. This, however, does not include my confession as to the existence of fossil sulphur bacteria. I think the curious structure of this ore deposit is due to the special properties of the pre-existing FeS_2 and carbonate-bearing shale by the subsequent action of metal-bearing solutions, from whatever source they may have originated.

The overwhelming abundance of replacement phenomena, even though of very small units at the limit of microscopic determination, is self-evident. Schloszmacher already gave some indications in that direction. A syngenetic deposition as mixed sulphide gels is inconceivable and seems to be adapted completely to a presupposed theory.

To elucidate this and in order to avoid recapitulation, I will give the most important points of my microscopic observations, followed in each case by Schneiderhöhn's points of view and by my conclusions.

(1) The spheres under consideration are chiefly composed of very small and rather tightly packed *idiomorphic* pyrite crystals. As these separate crystals, according to Schneiderhöhn, would be comparable with the original sulphur drops of the bacteria, it is evident that the FeS_2 gel could have crystallized only without solution and redeposition; otherwise the structure would have been obliterated. Moreover, if all the sulphides had been precipitated as mixed gels, how can the abundance of pure pyrite spheres free from other sulphides be explained, even in those areas where adjacent bornite and chalcocite are in excess? And why are coloform structures, so common in other gel-depositions, absent or scarce among the sulphides?

(2) The same spheres sometimes are built up of chalcopyrite, bornite or chalcocite grains, and seldom of sphalerite and galena, of the same dimensions and with the same forms as the pyrite crystals mentioned under (1). These individual sulphide grains, as well as the spheres as a whole, it must be inferred, are pseudomorphic after pyrite. In this respect it may also be emphasized that soft sulphides such as bornite and chalcocite, except in vugs, rarely exhibit crystal outlines. Hence, all these sulphides must have been formed, or at least redeposited, after the crystallization of pyrite was completed.

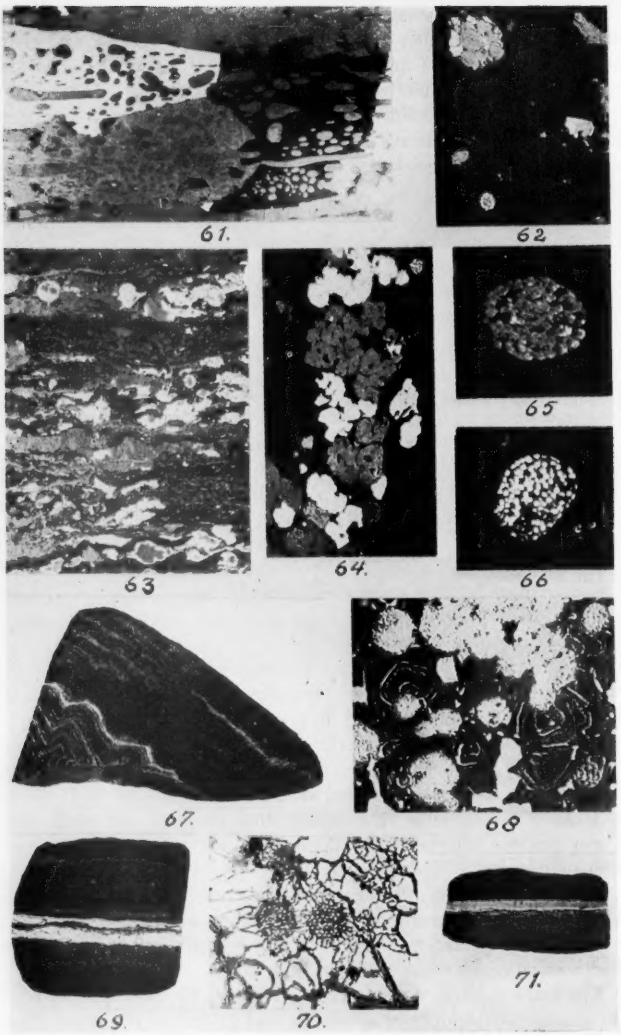

FIG. 61. Graphic intergrowths of pyrrhotite (white) and ilmenite (gray), magnetite (gray, somewhat lighter gray than ilmenite) and ilmenite and gangue (almost black). Hence three comparable intergrowths of eutectoid pattern in about .3 mm². Evje, Norway. × 900.

FIG. 62. Three different types of FeS_2 forms largely replaced by bornite (gray). Black is shale. Near the bottom of the Fig. the kernel of an original

(3) Larger disunited pyrite crystals here and there are convincingly pseudomorphically replaced by bornite, chalcocite, or chalcopyrite (Fig. 49). All transitional stages also occur.

Schneiderhöhn's statement that bornite is always primary and never shows crystal faces is absolutely correct. Part of the bornite is clearly younger and the crystal faces observed are inherited from pyrite.

(4) Marcasite is now scarce, but apparently it once was moderately present as shown by pseudomorphs of the sulphides of copper, copper-iron, lead and zinc, after marcasite. All these sulphides display close resemblance of the varying forms.

Crystallized marcasite already existed, it must be concluded, before the other sulphides cited could replace it (Figs. 73, 83).

(5) Spheres mainly composed of bornite or chalcocite occur where only the outer rim or part of it consists of very small idiomorphic pyrite crystals. Some grains of pyrite with impaired outlines, however, are embedded in the bornite or chalcocite. In view of the "atolls" described in a preceding paper this sort of structure is understandable by replacement. The relics of pyrite crystals with impaired outlines also point to this process.

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pyrite sphere consisting of tightly packed but very small pyrite crystals has been replaced by bornite (gray); only a rim of pyrite crystals resisted replacement. Near the top of the photo a larger pyrite concretion has been partially replaced; whereas near the right border the same has happened to a fragment of a pyrite crystal. Black, shale; white, pyrite remnants. Copper shale. Germany. × 550.

FIG. 63. Bornite (grayish white) in "crumpled" copper shale. Bornite replaces carbonate (gray); dark gray, shale. Copper shale. Germany.

FIG. 64. Bornite (gray) and galena (white) of exactly the same form and dimension as carbonate grains in the cement of the arkose sandstone. Black, sandstone. "Weisliegende." Copper shale. Germany. × 550.

FIG. 65. A sphere of tightly packed bornite crystals (gray) pseudomorphic after a pyrite sphere of the same structure. A few white pyrite remnants. Black, shale. Copper shale. Germany. × 1,700.

FIG. 66. A sphere of tightly packed chalcopyrite crystals (white) pseudomorphic after a similar pyrite sphere. Copper shale. Germany. × 1,300.

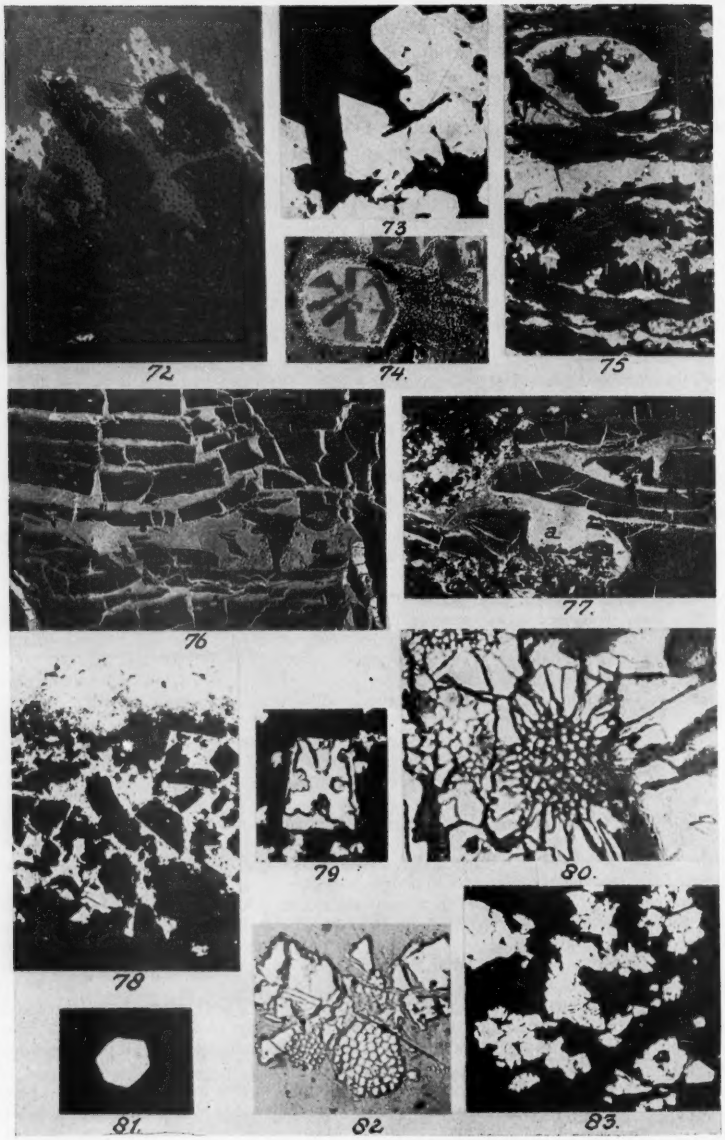
FIG. 67. "Crumpled" copper shale. Natural size. Black, shale; white, sulphide beds and blebs.

FIG. 68. An aggregate of pyrite spheres (white, somewhat pitted) and pyrite crystals (white, smooth surface) partly replaced by sphalerite (gray) with chalcopyrite inclusions (white). The ovoids indicate more or less the original FeS_2 structure. Rammelsberg, Germany. × 550.

FIG. 69. Polished surface of copper shale ore. Natural size. Thin beds of chalcopyrite (white) and of sphalerite (gray) in shale (black). Below the chalcopyrite beds the shale is spangled with fine chalcopyrite blebs (so called "Speise," barely visible). Above the sphalerite bed the shale is spangled with sphalerite blebs. Copper shale. Germany.

FIG. 70. Spherical concretions of chalcocite (gray) with many loosely packed pyrite remnants in a matrix of pyrite (white) cut by chalcocite veinlets. The chalcocite spheres with pyrite remnants are transitional stages to a complete pseudomorphism. "Dachklotz." Meggen, Germany. × 230.

FIG. 71. Finely bedded bornite (gray) and chalcopyrite (white) in shale (black). The polished surface below the fine chalcopyrite bed has innumerable small chalcopyrite blebs (barely visible). Many small chalcopyrite veinlets cut the bornite bed (not visible in photo.). Copper shale. Germany. Natural size.



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If these bodies were really fossil sulphur bacteria "on the verge of starvation," as held by Schneiderhöhn, it is inconceivable that the sulphur drops in the center did not crystallize to idiomorphic pyrite crystals. In well filled spheres the crystals are idiomorphic (Figs. 65, 66, 82, 85, 89, 90). Two examples of transitional stages from the "Dachklotz," in which no one doubts the secondary nature of the copper compounds, may illustrate this replacement (Figs. 70, 80).

(6) Spheres of FeS_2 of larger dimensions and with radial fibrous structure were observed, some of the fibers being guests for a sulphide copper compound. In certain cases smaller pyrite spheres are enclosed in the larger concretions and were selectively replaced (Fig. 51). Here again the later deposition of copper, after the crystallization of the FeS_2, is evident.

(7) A few massive chalcocite spheres occur, and in view of the structures and transitional stages already described in a previous paper it may be asserted that these chalcocite spheres are pseudomorphic after pyrite spheres (Fig. 52).

(8) More or less regular carbonate lenses, and generally with sharp and smooth outlines somewhat elongated and oriented parallel to the stratification, are common. They may be composed of calcite only or may show inter-

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FIG. 72. Carbonate (dark gray), sphalerite (gray, spickled), bornite (gray) and chalcopyrite (white) in toothed intergrowth under $\pm 60°$ with the bedding of the shale (black, near bottom of photo). Copper shale. Germany.

FIG. 73. Chalcocite crystals (white) pseudomorphic after marcasite. In shale (black). Copper shale. Germany. × 2,000.

FIG. 74. Synthetic replacement of pyrite by bornite (gray) and chalcocite (faint gray). Original crystal structure of pyrite preserved. × 200.

FIG. 75. Bornite (faint gray) as lenses and irregular beds. Remnants of carbonate (dark gray) are clearly distinguishable. In shale. One lath of chalcopyrite (almost white) in bornite lens. Copper shale. Germany. × 90.

FIG. 76. Part of a larger concretion (dark gray) with sphalerite (gray) filling cracks. Sphalerite replaces the gangue outward from "shrinkage" (?) cracks. Copper shale. Germany. × 200.

FIG. 77. Same as Fig. 76. Here however faint gray is bornite. Bornite replaces the carbonate (near *a*). Copper shale. Germany. × 200.

FIG. 78. Detail of Fig. 69. The bottom border of thin chalcopyrite bed from Fig. 69 at higher magnification. Chalcopyrite (white) replacing gangue (dark gray). Copper shale. Germany. × 200.

FIG. 79. Pyrite crystal (white, high relief) partly replaced by chalcocite (white). Transitional stage to complete pseudomorphism. Black, limestone. "Dachklotz" from copper shale. Germany. × 220.

FIG. 80. The original idiomorphic pyrite crystals composing a pyrite sphere are partly replaced and have impaired outlines. They are "lossely" packed. The surrounding coarser grained pyrite is traversed by chalcocite veinlets. Pyrite, white; chalcocite, gray. "Dachklotz" from copper shale. Germany. × 500.

FIG. 81. Crystal of galena (white) pseudomorphic after a pyrite crystal in shale (black). Copper shale. Germany. × 2,000.

FIG. 82. Pyrite and marcasite (both white) as remnants in chalcocite (faint gray). Initial stage of replacement of a tightly packed pyrite sphere. See also Fig. 80 as more advanced stage. "Dachklotz" from copper shale. Germany. × 190.

FIG. 83. Chalcopyrite aggregates (white) pseudomorphic after marcasite. Copper shale. Germany. × 200.

growths of calcite with dolomite or siderite. In the latter case the dolomite or siderite assumes well formed rhombohedrons against the calcite. These carbonate lenses are almost always enclosed in a small rim of coaly material.

On the other hand, sulphide lenses occur showing exactly the same characteristics as to form, dimension, distribution and intergrowths, with the carbonates. They exhibit clear evidence of selective replacement of calcite by sulphide, the rhombohedrons of dolomite or siderite remaining unimpaired (Plate 6, *h, j, k, l*). In addition, lenses composed partly of sulphides and

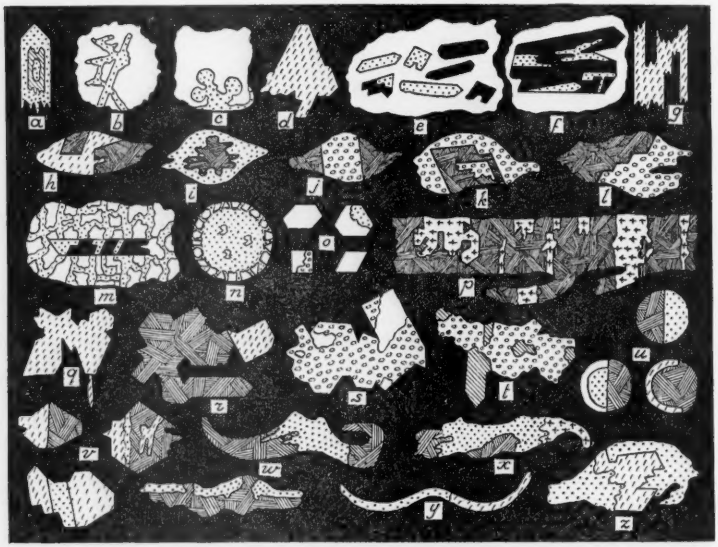

PLATE 6. Dark gray, shale or gangue; dark gray (mosaic), carbonate (*e.g.* Figs. *h, i, j, k, l, p*); gray (a mosaic, lighter than carbonate), sphalerite (*e.g.* Figs. *r, u, v, w, x*); white, pyrite; stippled, bornite; obliquely lined, marcasite (*e.g.* Figs. *a, t*); obliquely stippled, galena (*e.g.* Figs. *d, g, h, q, r, u, v, y, z*); white with small rings, chalcopyrite (*e.g.* Figs. *j, k, l*); various replacement structures of FeS_2 or carbonate by sphalerite chalcopyrite, bornite, chalcocite or galena. Copper shale. Germany. × 1,000 to 2,000.

partly of carbonates exhibit no irregularity and no break in the sharp and smooth outlines at the contacts. If the lenses are composed of one carbonate only the sulphides commonly show ragged outlines against the carbonates, obviously indicating replacement (Fig. 75).

Schneiderhöhn pointed out that the structural relations and the parageneses of sulphides and carbonates showed the unimportance of replacement phenomena, and concluded that they were of almost simultaneous formation.

If the sulphides and carbonates, however, had been deposited syngenetically as mixed gels, these relations would be difficult to understand, especially the smooth uninterrupted outlines of the lenses at the contacts (Plate 6, *h, j, k, l*).

That the different slimy sulphide gels and the carbonates would behave similarly during diagenesis and compression is hardly credible.

All of these relations, however, are conceivable and expectable if selective replacement and, as a final stage, complete pseudomorphism of sulphides, after pre-existing crystallized carbonate lenses, are accepted.

(9) Less frequently carbonate lenses are observed bordered by a more or less irregular rim of sulphides. Part of the sulphides may be composed of chalcopyrite, which is regarded by all investigators as secondary. These relations indicate an initial stage of replacement.

(10) In larger concretions, which may possibly be fossil fishes, rims and cracks may be filled by bornite, chalcocite, chalcopyrite or even sphalerite or galena (Figs. 76, 77). Locally the structures are convincing of metasomatism (Fig. 77). A definite age sequence of the sulphides in these larger concretions is clearly recognized, viz., sphalerite, bornite, chalcocite, chalcopyrite. Metasomatically these structures are normal.

Schneiderhöhn, however, indicated that this type of crack is always filled with chalcopyrite and added that other ore or gangue minerals do not occur in them. This, however, is incorrect. A syngenetic origin being admitted would lead us to the unacceptable conclusion that all of the sulphides had been redissolved and redeposited after their first deposition.

(11) In long thin plates of carbonate the fibers in some cases are arranged perpendicular to the stratification. Commonly the sulphide intergrowths within these carbonate plates exhibit a clear crystallographic connection with the carbonate fibers (Plate 6). Here it is obviously the host that localizes and guides the guest.

(12) The carbonate grains or fibers locally show a definite and constant angle with the stratification. Intergrowths of sphalerite, galena, bornite or chalcopyrite occur with corresponding jagged or fibrous structures making exactly the same angle with the bedding (Fig. 72). Wolff [6] has emphasized this fact and considered these relations as a proof of epigenetic origin.

(13) Chalcocite plays about the same role as bornite; it occurs in exactly the same spherical and lenticular forms as bornite, with this difference only, that bornite in general is obviously older.

In 1923 Schneiderhöhn stated that polished surfaces showed clearly that the chalcocite is younger than, and replaces, bornite. In 1926, however, he stated that as far as deposits of the copper shale type are concerned, he was inclined to consider both sulphides as simultaneous. Why these structures, especially for the Mansfeld deposit, should demand an exceptional structural interpretation is unaccountable, unless it was adapted to a presupposed theory.

(14) Chalcopyrite may be pseudomorphous after marcasite or after the pyrite spheres, preserving all their different internal structures. It is stated above that Schneiderhöhn regarded the chalcopyrite composing these much discussed spheres as primary. On the other hand he considered most chalcopyrite in beds, cracks or rims to be secondary. Hoffman, however, reported the newly formed chalcopyrite as having affected the whole ore deposit.

In some layers the bottom side of bornite beds may be wholly taken up by delicately stratified chalcopyrite without transecting structures being dis-

[6] Disc. Jahrb. d. Hall. Verbandes, 1919, pp. 21–40.

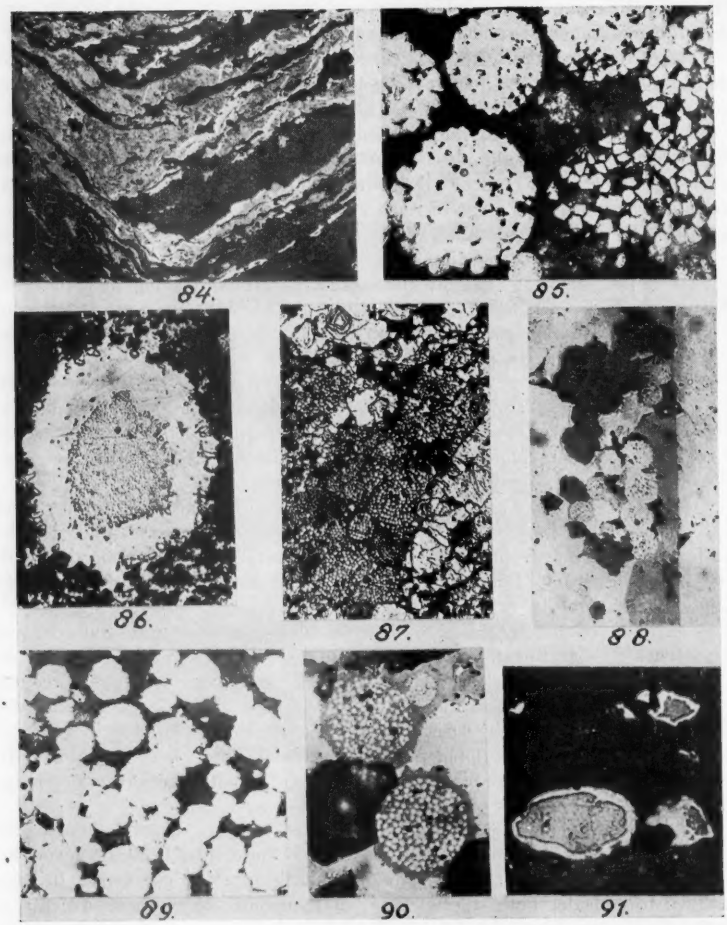

FIG. 84. Detail from Fig. 67. Dark gray, shale; gray, bornite with some covellite (somewhat darker gray than bornite); almost white chalcopyrite. Only the sulphide beds in the "limbs of the saddles rising to the left" contain an intergrowth of bornite and covellite, the "limbs rising to the right" contain intergrowths of bornite and chalcopyrite. Copper shale. Germany. × 55.

FIG. 85. Pyrite spheres composed of tightly packed idiomorphic pyrite crystals (white) in gangue (black). Meggen, Germany. × 1,000.

FIG. 86. Aggregate of small pyrite spheres (faint gray, in center, with relief) as remnants in a chalcocite concretion (white, smooth surface) with pyrite remnants along the border. Black, limestone, also partly replaced. "Dachklotz." Copper shale. Germany. × 55.

cernible (Fig. 71). Very fine gash-like forms of chalcopyrite, however, intersect the thin bornite layer, whereas very fine needles of chalcopyrite originating from these cross-cracks penetrate the bornite. The delicate stratification of this younger chalcopyrite bed is noteworthy. One sample of our collection (from which the polished surface of Fig. 71 was made) measures more than 20 inches, whereas the chalcopyrite layer is only .008 inch thick. Moreover, in some samples only sphalerite- and chalcopyrite-layers were observed free from other sulphides (Fig. 69). Above the sphalerite layer specks of this sulphide are disseminated abundantly, though hardly visible in the photograph; the shale beneath the chalcopyrite layers, on the contrary, is spangled with chalcopyrite specks. Most all spheres, especially those of Mansfeld, are composed of tightly packed chalcopyrite units pseudomorphic after the small pyrite crystals. In addition, the carbonate at the bottom of the chalcopyrite layers is convincingly replaced (Fig. 78).

It may be concluded that this chalcopyrite regarded by all investigators as being secondary is remarkably and delicately interstratified and that at least part of the chalcopyrite of the so-called fossil sulphur bacteria must be secondary as well.

(15) Covellite is rarely a local constituent of the typical spheres. It is immaterial whether this covellite is primary or secondary if we look at it from a purely structural sense without genetic considerations. This covellite may occupy the center of the typical spheres with the rim consisting of idiomorphic pyrite crystals, but a few impaired pyrite grains may be embedded in the covellite. It is always younger than bornite and occurs in finely folded material, often called "crumpled" copper shale. It presumably was formed after the folding (Figs. 67, 84). Being the guest it may be considered as pseudomorphous after pyrite spheres. This kind of structure again gives conclusive evidence of the exactness with which delicate structures may be preserved during replacement.

(16) In transition zones where sphalerite and bornite occur in direct association, the sphalerite units are commonly, clearly, partly replaced by bornite (Fig. 91).

(17) In a somewhat higher or lower level than the normal ore bed, spheres of FeS_2 and lenses of carbonate such as those described above may be absent. Instead, globular and smaller carbonate grains are abundant. In such cases, sphalerite, galena, bornite or chalcocite assumes the same forms, has identical

FIG. 87. FeS_2 from Rio Tinto, Spain, etched with HNO_3. Pyrite spheres and pyrite "dust" in shale (black). × 550.

FIG. 88. Pyrite spheres (composed of tightly packed idiomorphic pyrite crystals in a groundmass of coarse pyrite (white)); pale gray, linnaeite?; dark gray, sphalerite. Redruth, Cornwall. × 210.

FIG. 89. The well-known pyrite spheres (white) in sphalerite (gray). The internal structure of these spheres (very tightly packed idiomorphic pyrite crystals) becomes only visible after etching. Meggen, Germany. × 400.

FIG. 90. Same as Fig. 88. The internal structure of the pyrite spheres now becomes clearly visible. White, pyrite; gray linnaeite?; black, sphalerite with internal reflections. Redruth, Cornwall. × 1,800.

FIG. 91. Sphalerite (gray) surrounded and partly replaced by bornite (white) in shale (black). Copper shale. Germany. × 200.

dimensions, and shows comparable distribution (Fig. 64). Once again it may be concluded that pseudomorphism of sulphides after carbonate grains has occurred.

A syngenetic precipitation of mixed gels is improbable since it seems incredible that all sulphides would assume in all beds everywhere, exactly similar, though divergent, forms and dimensions as the carbonates. The absence of coloform intergrowths of different sulphides in one single grain (Fig. 64) would be unusual also.

(18) Sphalerite and galena were observed as pseudomorphs after marcasite (Plate 6, *d, q, r, t*) after pyrite (Fig. 81) and after carbonate lenses as described under (8), showing the same boundary relations.

(19) Normal replacement structures of text-book clarity after sulphides, or sulphides and carbonates, are discernible everywhere in disturbed areas. The kind of intergrowths and the succession in sulphide replacements is the same as in undisturbed parts.

(20) In the "Dachklotz," which is the hanging wall limestone of the copper shale, the secondary nature of the sulphides (FeS_2 excluded), has never been doubted. Here too, exactly the same replacement structures of FeS_2 in all its varying forms are clearly demonstrated (Figs. 86, 79, 80, 82, 70).

(21) In the "Weiszliegende," which is the bleached arkose sandstone forming the footwall, locally rounded grains of quartz, feldspar and rarely rutile, ranging from .2 to .5 mm diameter, occur side by side with grains of bornite, sphalerite, galena, chalcocite and tennantite. Pyrite of this form was never observed. The grains may also consist of a nucleus of gangue surrounded by sulphide, or may show irregular intergrowths indicating metasomatism (Figs. 57, 58, 59, 60). Dimension and form of gangue plus sulphide, it must be pointed out emphatically, coincide exactly in these cases with those of the original gangue grains.

We are asked to regard these structures as syngenetic depositions, reflecting Schneiderhöhn's view that the ore content of this type of ore also would be primary.

In summary, the abundance of pseudomorphisms and other replacement structures are convincingly forcing the conclusion that the sulphides (except FeS_2) in the copper shale are epigenetic. The origin of the solutions containing copper, lead, and zinc, and the path followed by them, were omitted from the discussion. FeS_2 and the different carbonate forms existed prior to the entry of the solutions, being present in the slate in a crystallized state before the ore solutions began their attack. A syngenetic origin as mixed gels and the existence of fossil sulphur bacteria, as advanced by Schneiderhöhn, are regarded as highly improbable, morphologically, physiologically, chemically and from the standpoint of ore genesis.

Advice and suggestions of Prof. Dr. Fr. A. J. Kluiver, microbiologist, have been of great value in the preparation of this paper, especially with respect to the peculiarities of sulphur bacteria, and his help is gratefully acknowledged.

INSTITUTE OF TECHNOLOGY,
DELFT, HOLLAND,
March 6, 1946.

A COTANGENT RULER FOR SIMPLIFYING THE GRAPHIC SOLUTION OF PROBLEMS IN STRUCTURAL GEOLOGY.[1]

WALTER S. WHITE.

ABSTRACT.

The cotangent ruler is a device for measuring directly the dip of contoured surfaces, or, conversely, for constructing contours that represent planes of known dip. It greatly simplifies the graphic solution of problems in structural geology, and has several specialized applications to problems commonly encountered in mining geology and areal geologic mapping.

INTRODUCTION.

In the course of a wartime program of geologic mapping in the Michigan copper mines, many thousands of fissures and faults were observed and their attitudes recorded. Study of these data required the solution of countless problems involving the projections and intersections of dipping planes. For the solution of most of these problems, graphic methods,[2] aided by the device described below, were found to be more efficient than the use of stereographic or equal area nets, because the latter methods only give angles and these must be transferred to the worksheet. The cotangent ruler was developed to eliminate certain steps in the standard graphic methods, and the writer believes it saved him several days out of a period of 2 or 3 months. Its accuracy in geologic problems is well within the limits of observational error.

The writer thanks G. H. Espenshade and R. S. Cannon, Jr., of the Geological Survey and Prof. M. P. Billings of Harvard University for critical review of the manuscript and for many helpful suggestions. The writer wishes to state that he has not made an exhaustive search of the literature and to acknowledge that a similar device may have been previously described. It seems worthwhile nevertheless to record for the benefit of mining geologists a method that has been used effectively in solving many types of structural problems that are commonly met in geologic work.

In the graphic solution of problems in structural geology, extensive use is made of lines that are, in effect, structure contours. Most problems involving dipping planes and their intersections can be readily solved by using contours at two altitudes. The vertical interval (contour interval) between the altitudes may be any convenient distance, but the interval chosen must be constant throughout a given solution. A dipping plane is represented in the horizontal plane of the paper by two parallel lines (contours); the horizontal distance between lines is directly proportional to the cotangent of the dip of

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Willis, B., and Willis, R.: Geologic Structures, 3rd edition, pp. 338–345, New York, 1934. Lahee, F. H.: Field Geology, 4th edition, pp. 683–695, New York, 1941. Billings, M. P.: Structural Geology, pp. 439–453, New York, 1942.

LIBRARY

the plane, *e.g.* a plane dipping 20°, with a vertical interval of 1 inch, is represented by two parallel lines 2.75 inches apart (1″ × Cot. 20° = 2.75″). Where the dip is steep, the lines, like ordinary contours, are closer together than where the dip is gentle.

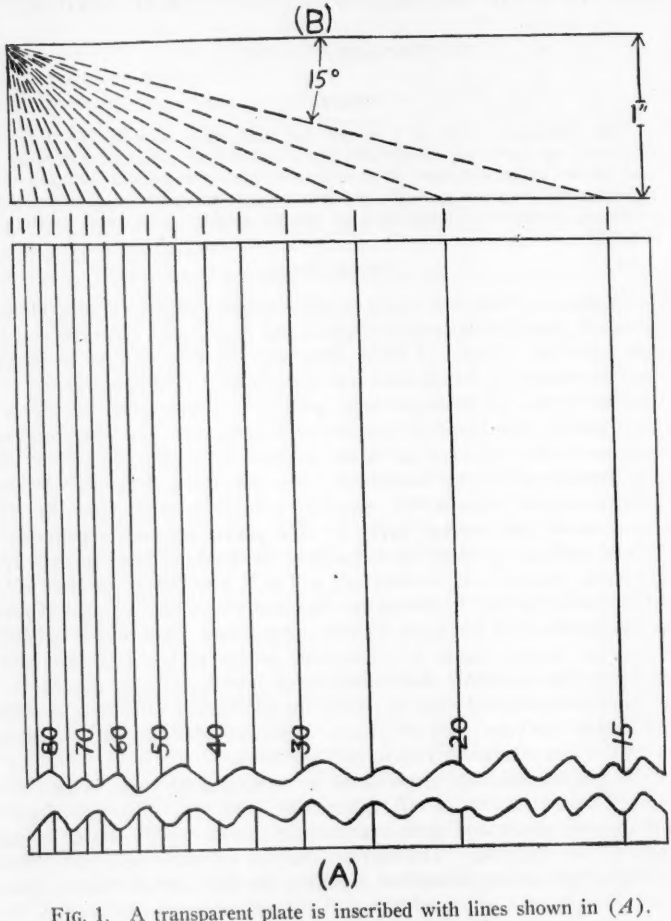

FIG. 1. A transparent plate is inscribed with lines shown in (*A*). (*B*) shows principle of construction.

Conventional graphic solutions require the construction of two or more vertical cross sections in which vertical angles are laid out or measured. This operation can be eliminated by the use of the cotangent ruler described below and pictured in Fig. 1.

DESCRIPTION OF COTANGENT RULER.

A transparent rectangular plate of acetate or vinylite (4″ × 7″ is a convenient size) is inscribed with parallel lines whose distances from one long edge (the 90°-edge) of the plate are equal to a constant times the cotangent of angles less than 90°. In Fig. 1, for example, these distances are equal to 1 inch times the cotangents of angles from 90° to 15°; the line representing a dip of 45° (Cot. 45° = 1) is one inch from the 90° edge (Cot. 90° = 0), and the line representing a dip of 20° (Cot. 20° = 2.75) is 2.75 inches from the 90° edge. The horizontal distance between the two lines (contours) required to represent a dipping plane is given directly by the distance from the 90° edge of the plate to the line whose degree value numerically equals the known dip of the plane. The plate illustrated in Fig. 1 has a line for every fifth degree of dip; intermediate angles are readily determined by interpolation.

The cotangent ruler is similar in principle to the slope scales [3] widely used to facilitate the reading of military maps. Slope scales, commonly printed along the edges of a card, show by short ruled lines the spacing of contours for selected values of slope on maps of a given scale and contour interval. The cotangent ruler differs in several important respects. The combination of a ruling edge with a cotangent scale provides a wider range of usefulness to geologists than would a slope scale. Military slope scales are calibrated in per cent grade, and rarely give gradients of more than 50 per cent. Lastly, the cotangent ruler differs in the use of a common reference line (the 90° line) for all horizontal measurements, which permits greater accuracy in interpolation than is possible with the selected intervals of the common slope scale. It is less convenient than a slope scale for reading slopes on topographic maps in that a number of different map scales and contour intervals cannot be combined in a single device.

The upper plate of a special protractor devised by McKinstry [4] is identical in principle and construction with the cotangent ruler described here, but its combination with another plate gives it less general application and utility.

USE OF THE COTANGENT RULER.

To use the device, the strike of the plane is first plotted as a line. The line on the plate whose degree value is equal to the dip is laid over the plotted line with the 90°-edge on the down-dip side of the plotted line. Using the 90°-edge as a straightedge, another line is drawn parallel to the first; this is the other line (contour) required to define the plane. Solutions are carried out in the conventional manner, but the steps involving construction of vertical cross-sections and measurement or laying-off of vertical angles are eliminated.

The short edges of the plate may be used as scales to determine the plunge of lines. On a line representing the horizontal projection of a plunging line, two points represent the intersection of the plunging line with the

[3] Fisher, D. J.: Some dip problems. Bull. Amer. Assn. Petroleum Geologists, vol. 21, p. 344, 1937.

[4] McKinstry, H. E.: A protractor for plotting dips on inclined sections. ECON. GEOL., vol. 18, pp. 393–397, 1923.

upper and lower horizons. If the distance between the points is known, the plunge is given directly by measurement from the 90°-edge along one of the short edges of the plate. If the plunge is known, the distance between the points can be plotted in the same way.

The device may be used to simplify many common graphic solutions. Some examples are presented below; in each the strike and dip of the planes involved are represented by the conventional symbol.

A. Given the attitude of two planes represented by the strike and dip symbols at *B* and *C* (Fig. 2), to determine the plunge of their intersection:

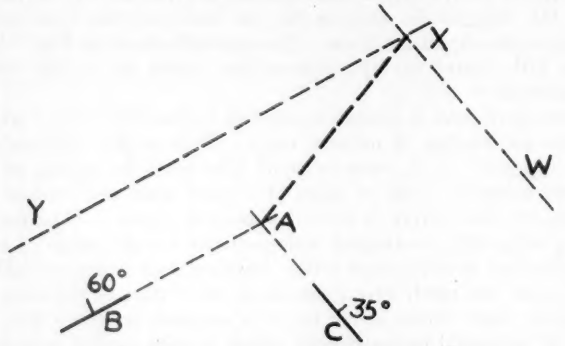

FIG. 2. Intersection of two planes.

1. Project the strike lines to their intersection at *A*.
2. Lay the 60° line of the plate over line *AB* of the drawing and rule line *YX* against the 90°-edge.
3. Lay the 35° line of the plate over line *AC* of the drawing and rule line *WX* against the 90°-edge.
4. Draw line *AX*, which is the horizontal projection of the intersection and which gives its bearing and direction of plunge.
5. Laying one of the short edges of the plate against *AX*, with *X* at the 90° line, *A* falls at 34° (by interpolation between 30° and 35°). This is the plunge of the intersection in degrees of vertical angle.

B. Given a plane whose attitude is represented by the strike and dip symbol at *B* (Fig. 3), to determine the apparent dip of the plane in a vertical section not at right angles to the strike of the plane:

1. Project the strike of the plane to its intersection *A* with the section line *AX*.
2. Lay the 50° line of the plate over strike line at *B* of the drawing and rule line *XY* against the 90°-edge.
3. Laying one of the short edges of the plate against *XA*, with *X* at the 90° line, *A* falls at 45°. This is the apparent dip in the vertical section.

C. Given the dip and strike of a plane and the bearing of a plunging line lying in the plane, to find the angle of plunge:

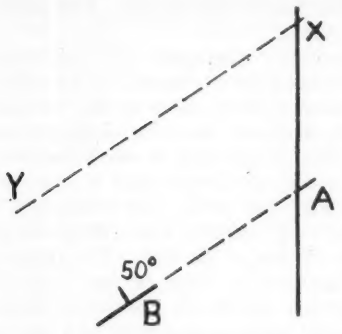

FIG. 3. Apparent dip of a plane in section.

Solution same as B.

D. Given the attitude of a plane represented by the strike and dip symbol at *C* (Fig. 4) and the plunge of a line lying in the plane, to find the bearing of the line (In the problem below, the line plunges 30° in a northeasterly direction, but its exact bearing is not known):

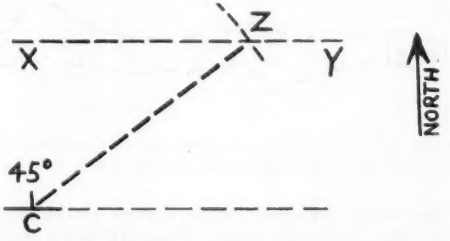

FIG. 4. Bearing of a plunging line in a plane.

1. Lay the 45° line of the plate over the strike line at *C* and rule *XY* against the 90°-edge of the plate.
2. Locate the point *Z* either by a compass intersection or by experiment—it is the only point on *XY* to the northeast of *C* whose distance from *C* equals the distance on the plate between the 90°-edge and the 30° line.
3. Draw line *CZ*, whose bearing is the direction of plunge sought (N. 55° E.).

Limitations.—The cotangent ruler illustrated in Fig. 1 is useful for the graphic solution of general problems in structural geology in which none of the vertical angles to be measured is less than 14°. A second plate of the same size, representing a vertical interval (contour interval) of ¼ inch, may be used for angles as low as 4°. Other plates could easily be made for still lower angles, but on such plates the lines representing higher angles become very crowded and the chance for error increases where a problem

involves both high and low vertical angles. Obviously, only one plate can be used in any one solution.

Specialized Applications.—Cotangent rulers can be made that will serve a specific purpose. A special plate is useful, for example, in mines where the vertical distance between levels is more or less constant. If plan maps of a particular scale are commonly used for keeping a record of geologic information, a special plate can be made in which the constant to be multiplied by the cotangent in spacing the degree lines is equal to the vertical interval between levels at the map scale used. For example, a plate with a constant of two inches could be used in a mine where the levels are 100 feet apart and the map scale used is 50 feet to the inch. The plate so constructed can be used to show the identity of a plane on two levels without an elaborate construction, or to predict quickly the position of a plane structure on one level from its attitude and position on another, as in the following example:

E. Given the strike and dip of a plane on one level (Fig. 5), to predict its probable position on the level below.

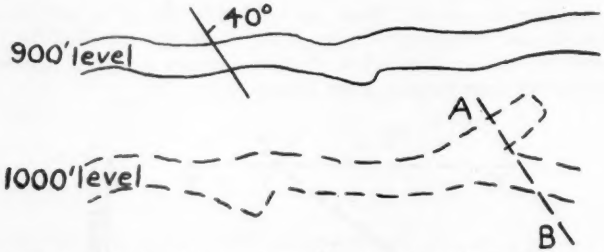

FIG. 5. Projection of a plane from one mine level to another; plan view, levels 100 feet apart vertically, scale 1 inch equals 100 feet.

1. Lay the 40° line of the plate over the strike line of the plane, and rule line *AB* against the 90°-edge of the plate. Line *AB* is the line sought.

Note that in projecting up the dip to a higher level, the 90°-edge is placed on the up-dip side of the strike line.

F. Given the position and strike of a plane on two levels, to determine its dip:

Solution is the converse of E.

A cotangent ruler adapted to the scale of a topographic map may be useful in the compilation and interpretation of geologic information. For a topographic map of given scale and contour interval a cotangent ruler can be constructed in which the constant (vertical interval) is equal to the contour interval of the map at the scale of the map. A constant of 1/20 of an inch is used, for example, if the contour interval is 100 feet and the map scale is 1 inch equals 2,000 feet.[5] In this example a plate 1 inch wide can be used

[5] It is not necessary to use the interval between every contour. On maps of small scale with closely spaced contours, it may be found desirable to construct the cotangent ruler for use with every fifth or tenth contour. The principal use of the ruler on such maps would be found in areas where the dips are very gentle.

for vertical angles as low as 3° and can be conveniently carried and used in the field. The short edge of the ruler serves as a slope scale to give directly the gradients of contoured surfaces on a topographic or structure contour map. The most valuable use of the ruler in areal mapping, however, is in the prediction and interpretation of outcrop patterns in areas of low dip and considerable relief. Given the strike and dip of a plane, properly spaced structure contours on the plane are drawn directly with the aid of the cotangent ruler, and the intersection of the plane with the surface of the ground is plotted in the conventional manner.[6] Given the outcrop pattern of a plane structure, the strike and dip can be determined by reversing this procedure.[7]

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.
March 15, 1946.

[6] Willis and Willis, *op. cit.*, pp. 360–363. Lahee, *op. cit.*, pp. 604–606. Billings, *op. cit.*, pp. 415–418.

[7] Lahee, *op. cit.*, pp. 672–673.

ON THE NATURE OF REPLACEMENT.

G. VIBERT DOUGLAS, N. R. GOODMAN, AND G. C. MILLIGAN.

"The process (of metasomatism) is not as yet fully understood" (*Bateman, 1942*).
"Where? whither? why? how?—these questions cover all philosophy" (*Joubert*).

ABSTRACT.

Metasomatism is understood to be the process by which mineral substance is introduced, by liquids or gases, into pre-existing substances and deposited there at the expense of those substances. This implies the introduction and removal of material. Replacement probably involves a number of processes but only three are considered: pseudomorphs, hydrodynamics and atom shunting. Some of these notions were tested by experiments. The authors do not claim to have explored the whole subject of metasomatism.

MINERALOGISTS, petrologists, paleontologists, stratigraphers, and mining geologists are confronted with the problem of the nature of replacement. Many subscribe to the fore-going frank statement by Bateman. Geologists have accepted, practically without question, metasomatism and its more descriptive synonym "replacement." The writers do not suggest that these terms should not be accepted, but submit that it is a dangerous practice to accept a descriptive word as self-explanatory, while admitting that we do not understand fully the process which this term describes. An analogous condition existed in the scientific thoughts of the early chemists, whose ready acceptance of the term "phlogiston" succeeded in disposing of a difficult problem, with the result that the true nature of heat was hidden for many years.

Metasomatism, or replacement, as used in this paper is understood to be the process by which mineral substance is introduced, by liquids or gases, into pre-existing substances and deposited there at the expense of those substances. This implies the introduction and removal of material. It does not mean the filling of existing spaces (porosity, cracks, etc.), nor crystal growth in yielding material where nothing has been removed. Replacement probably involves a number of processes. The present authors consider three:

(1) Pseudomorphs
(2) Hydrodynamics
(3) "Atom shunting."

Fig. 1 shows camera lucida drawings of two specimens of petrified trees. No. 1 is from the Joggins Shore of Nova Scotia. The volume once occupied by woody fabric is now seen to be composed of a mosaic of predominantly quartz grains. No. 2 exhibits the replacement of the wood fibers by carbonates and the preservation of the annular rings. No. 1 is an example of hydrodynamic replacement. No. 2 is an example of chemical replacement.

Pseudomorphs.—The formation of a pseudomorph implies the removal of an already formed mineral, and the filling of the resulting open space by the "replacing" mineral, which exhibits the crystal habit of the original.

Hydrodynamics.—The hydrodynamical conception involves the softening and subsequent removal of the host rock and the deposition of the "replacing" mineral in the open space so produced.[1] In order to test this notion the following experiment was carried out: Identical specimens of the Precambrian slates of Nova Scotia were subjected to continuous attack by warm acid and alkali solutions for 360 hours. The chemical composition of these slates is shown in Table 1.[2] The results of the experiment are shown in Table 2.

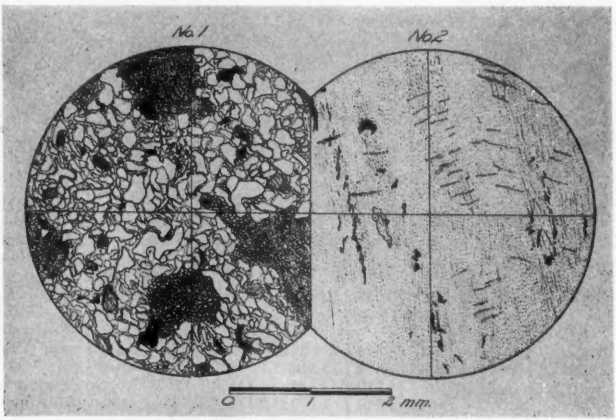

FIG. 1. Camera lucida drawings of two specimens of petrified wood. No. 1. Tree from Joggins Shore of Nova Scotia. Composed chiefly of slightly angular quartz grains with other detrital minerals. No. 2. Locale of this specimen not known. Composed of carbonate with carbonaceous material shown in black. Preservation of annular rings discernible. Both thin-sections cut normal to axis of tree.

This experiment shows that an attack on slate rock by flowing solutions, at normal pressure and temperatures below boiling, will bring about a disintegration of the rock fabric, which is carried away either in solution or by flushing of the fine particles.

Atom Shunting.—Bateman[3] puts forward the following problem: "Replacement involves the necessity of continuing supplies of new material and removal of the dissolved material. This question becomes more pointed in the

[1] Douglas, G. V., The hydrodynamical factor in ore deposition. Am. Jour. Sci., Daly Volume, 243-A: pp. 122–134, 1945.

[2] Douglas, G. V., Milner, R. L., and MacLean, J. H., The deposition of the Halifax Series. Nova Scotia Dept. of Mines, 1936.

[3] Bateman, Alan M., Economic Mineral Deposits. John Wiley and Sons, New York: pp. 92–115, 1942.

TABLE 1.

CHEMICAL COMPOSITION OF PRECAMBRIAN SLATES OF NOVA SCOTIA, HALIFAX SERIES (Douglas, Milner & MacLean, 1936).

	[1]
SiO_2	61.05
Al_2O_3	22.36
Fe_2O_3	4.98
MgO	0.73
CaO	0.43
Na_2O	3.14
K_2O	3.25
H_2O-	0.36
H_2O+	2.90
S	0.80
	100.00

[1] Average of two slates—Halifax Series.

TABLE 2.

No.	Solution	Concentration % by Weight	Average Temp. over 360 hr. Period ° C.	Original Weight of Specimen gms.	Weight after 360 hrs. gms.	Loss in Weight gms.	% Loss	Remarks [6]
1	HNO_3	70	67	18.859	16.221	2.638	13.99	Specimen split along cleavage. Definite softening. Many small fragments fell to bottom of beaker
2	HCl	36	69	26.258	22.987	3.271	12.46	Some material in bottom of beaker. Definite softening of specimen
3	H_2SO_4	95	74	28.326	27.829	0.497	1.75	No apparent effect
4	NaOH	35	72	25.084	23.550	1.534	6.12	No visible effect
5	KOH	45	66	34.750	33.335	1.415	4.07	No visible effect
6	$Fe_2(SO_4)_3$	Sat.	58	4.929	4.770	0.159	3.23	Some rusting of specimen

Note: These were most concentrated solutions available.

case of an unfractured pyrite cube that is undergoing replacement by compact chalcocite from the outside toward the center by means of a liquid solution at normal temperature. First, the faces of the cube are replaced, say to a depth of one-quarter of its diameter. Then, the replacing copper must penetrate a dense layer of chalcocite in order to arrive at the interior front of replacement, and the dissolved iron from the pyrite must escape through the same layer of compact chalcocite." This challenging problem is convenient for work in the laboratory from the point of view of both temperature and pressure, for it may be considered a product of secondary sulphide enrichment where the conditions of temperature and pressure are, or closely approach, those of surface conditions.

A single-cell crystal of iron pyrite was drawn to scale accepting the cell dimensions of W. L. Bragg [4] and the atomic radii of V. M. Goldschmidt [5] (Fig. 2). The black sphere outside the crystal represents an atom of copper

[4] Bragg, W. L., Proc. Roy. Soc. 89: p. 468, 1914.
[5] Goldschmidt, V. M., Trans. Far. Soc., 258, 1929.

drawn to the same scale. The iron atoms could easily be replaced by the copper on the exposed face of the cube; but normal crystals contain many cells such as the one shown in Fig. 2. The problem then becomes one of passing the atom of copper through the space lattice of pyrite to replace the iron.

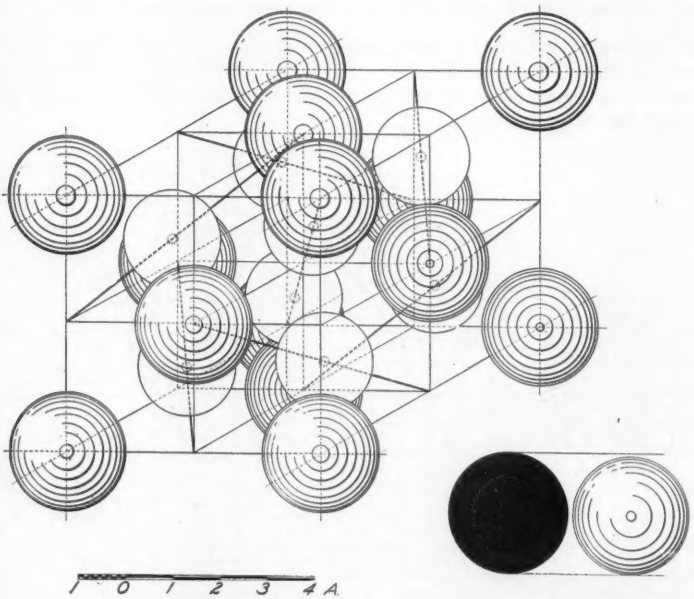

FIG. 2. Three-dimensional drawing of the space lattice of iron pyrite. (Bragg, 1914) Iron—*line shaded*. Sulphur—*white*. Copper—*black*. Copper atom shown outside space lattice with iron atom for comparison of size only. Double lines are position lines of sulphur atoms and do not represent double bonds.

Many and conflicting are the modern views concerning the nature of the atom. Some consider that the atoms act as hard shelled spheres and that the field of force of the electron shells of one atom cannot be entered by the electron shells of another atom. Others think of the atom as consisting of a nucleus surrounded by electrons and believe that the revolving electrons of one atom can pass inside the orbit of the outer electrons of another atom. A third suggestion is that the electron shells are statistical surfaces, and, as such, may be visualized as having a jelly-like nature and so could be pushed aside by another atom. In view of the conflicting ideas as to this prime consideration, it became necessary to make an assumption as to which picture would be accepted, and proceed on the basis of that assumption; if it failed to stand up in the face of critical tests then it would be necessary to alter these views. The following was assumed:

(1) That the atoms consist of a nucleus surrounded by electron shells.
(2) That the electron shells cannot be passed through by the electron shells of other atoms.
(3) That although the electron shells may not be spherical, the mean atomic radii of Goldschmidt are accepted; and thus the atoms are represented graphically in a space lattice as spheres.

The maximum available free space between atoms in the space lattice of iron pyrite as shown in Fig. 2 is 1.3 Å. Therefore, on the basis of the above assumption, a copper atom, having an atomic diameter of 2.56 Å, cannot pass through this space lattice.

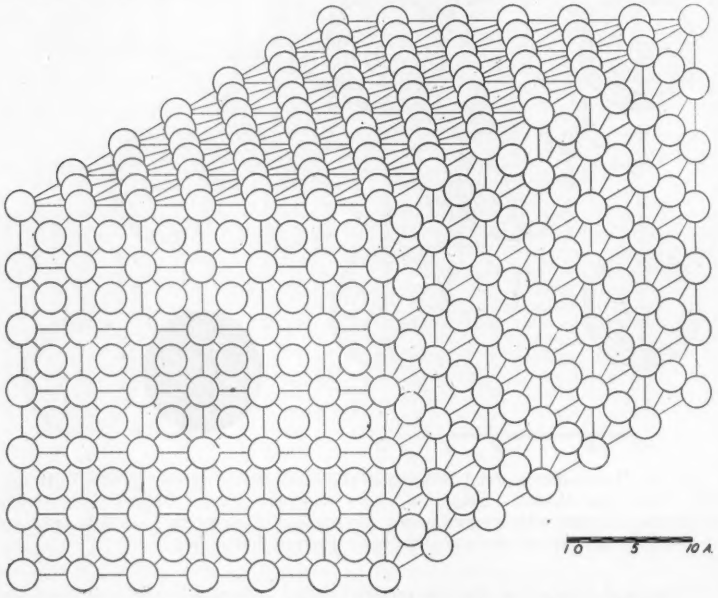

FIG. 3. 216-cell crystal of iron pyrite. Iron atoms only are shown.

Fig. 3 shows a 216-cell crystal of iron pyrite, with only the iron atoms represented. Outstanding in this drawing is the existence of planes on which the iron atoms are positioned. Any one iron atom, situated on the corner of a cell, is surrounded by eighteen neighboring iron atoms (Fig. 4) and could be considered as able to move to the position occupied by any one of its eighteen neighbors without disturbing the sulphur atoms.

This suggests the possibility of a system of "atom shunting." By this is meant, that the entry of a copper atom (diam. 2.56 Å) would shunt the line of iron atoms along and displace one atom of iron (diam. 2.50 Å) from the opposite face. It is not necessary that the "shunting" process be in a straight

line, for, as has been pointed out, any one iron atom could move to the position of any one of its eighteen neighbors. Thus the line of movement of the atoms might change at any time without altering the over-all results of this picture. It is not visualized that the entry of the copper atom causes all the iron atoms to move simultaneously, but rather that, as a locomotive shunts a train and the impact passes from car to car, so in the crystal the atoms move one after the other. The force required is not that which would be necessary to break all the bonds at once but only that required to break the bonds of one atom.

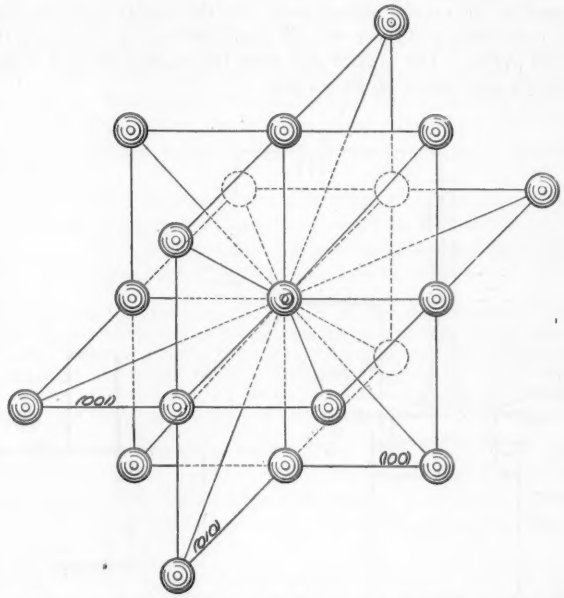

FIG. 4. Relation of neighboring iron atoms to an iron atom on the corner of cell in the interior of a crystal of pyrite.

The entry of the copper atom does not have to supply all the forces required to displace the iron atom. In experiments conducted, iron was removed from a crystal of pyrite by chemical reaction on one face while copper was introduced at the opposite face. This can be thought of as amounting to a push effect from the copper, assisted by a pull effect resulting from the chemical removal of the iron.

The following experiments were conducted to test the hypothesis of "atom shunting":

Experiment No. 1.—A crystal of iron pyrite was suspended in a saturated solution of copper sulphate for 240 hours at a temperature of 50–60° C. There was no discernible alteration of the crystal.

Experiment No. 2.—A crystal of iron pyrite was suspended in a solution made up of copper sulphate, ferrous sulphate, ferric sulphate and very dilute sulphuric acid for 480 hours at a temperature of 50–60° C. There was no discernible alteration of the crystal. This solution was designed to simulate the composition of the solutions responsible for the secondary sulphide enrichment at Rio Tinto, in the province of Huelva, Spain.

Experiment No. 3.—A crystal of iron pyrite was set in a bath of copper sulphate with the cathode of a 6 volt dry cell series connected to the crystal. The anode, a copper grid, was placed below the crystal in the bath. Metallic copper plated on the crystal immediately; but the copper could be peeled from the face of the crystal and there was no noticeable reaction between the copper and the iron pyrite. The crystal had been thoroughly cleaned with acid before the copper was plated on its surface.

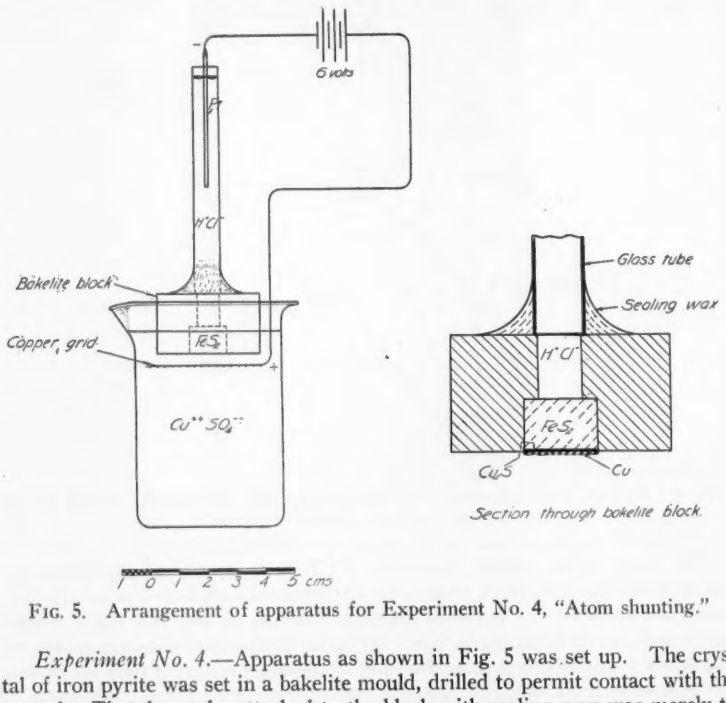

FIG. 5. Arrangement of apparatus for Experiment No. 4, "Atom shunting."

Experiment No. 4.—Apparatus as shown in Fig. 5 was set up. The crystal of iron pyrite was set in a bakelite mould, drilled to permit contact with the crystal. The glass tube attached to the block with sealing wax was merely to increase the amount of solution above the crystal so that there would be sufficient to test, and also to prevent evaporation overnight causing the system to stop. This glass tube was spoken of as the "well." The well was filled with distilled water rendered conducting with one drop of hydrochloric acid. The platinum cathode of a 6 volt dry cell series was placed in the well, but

not in contact with the crystal. The bakelite block was immersed, to approximately half its depth, in a beaker of saturated copper sulphate solution, with a copper grid anode placed just below the iron pyrite. Minute bubbles, probably hydrogen, were given off from the cathode. Soon after the system started the solution from the bottom of the well gave a strongly positive reaction when tested with potassium thio-cyanate from the presence of iron. As no bubbles were observed rising from the bottom of the well, it is thought probable that the chlorine reacted with the iron of the crystal to form iron chloride, thus removing the iron and causing a pull effect for "atom shunting." Metallic copper plated on the face exposed to copper sulphate solution. The specimen was removed after the apparatus had been in continuous operation for ninety hours. The copper plate was carefully scraped from the surface of the iron pyrite. Under this copper plate the crystal had apparently been altered; it now had a dark gray, almost black, appearance. On examination under the microscope, with reflected light, the film over the pyrite was tentatively identified as chalcocite.

A second specimen of iron pyrite was treated in the manner described above, and without being tested in any way, was sent to Prof. M. A. Peacock, of the University of Toronto, to have the dark film identified by x-ray powder photograph. The reply from Prof. Peacock was as follows:

"R. M. Thomson carefully scraped some of the black material from your polished section and obtained an x-ray powder photograph which proved to be made up of two patterns, namely ordinary pyrite and isometric chalcocite or beta chalcocite, as it is sometimes called. The pyrite pattern is much the stronger component while the indications of beta chalcocite are weak but distinct. This suggests to me that the film of copper sulphide must be very thin indeed."

During the preparation of the specimen for Prof. Peacock, the system was stopped every thirty hours, and the copper plate was scraped from the surface of the crystal to ascertain if the film was developing as desired. There was an easily discernible, progressive, darkening of the film, indicating that the chalcocite was thickening.

These experiments have demonstrated that iron pyrite can be replaced by chalcocite in an electrical circuit. The use of an electrical circuit is justified by two facts: (1) The replacement of metallic minerals is always in accord with the electrochemical series. For example, in nature, chalcocite always replaces pyrite and not *vice versa*. (2) It is a well known fact that electrical currents are present in the earth's crust in the vicinity of ore bodies; which fact is utilized in the Schlumberger method of geo-physical prospecting.[6]

In conclusion, the authors submit that the problem of replacement has been enunciated and possibly a beginning has been made in its explanation.

The authors wish to acknowledge, most gratefully, the co-operation, suggestions and criticisms of the following: Prof. Charles Palache and Prof. L. C. Graton of Harvard University; Prof. M. A. Peacock and Dr. F. Gordon Smith of University of Toronto; Prof. C. C. Coffin of Dalhousie University; and D. G. Ellis, graduate student of Dalhousie University. This does not imply that the above share the views expressed in this paper.

[6] Eve, A. S., and Keys, D. A., Applied Geophysics. Cambridge, 1929.

DISCUSSION AND COMMUNICATIONS

LEAD–SILVER MINERALIZATION IN THE CLARK FORK DISTRICT.

Sir: A recent article of the above title in ECONOMIC GEOLOGY [1] contains a discussion of the determination of microscopic ore minerals by means of polarization colors, tarnishing reactions, color of polished surface, hardness, etc. I am confident that such minerals can be identified by simple, inexpensive means. However, the identification is not as simple as indicated by Mr. Anderson in this article. For example, the properties used by him to determine semseyite also indicate jamesonite, meneghinite, plagionite, weissite and zinkenite. The following table shows the listed variations in the polarization colors of this group of minerals:

POLARIZATION COLORS

	Farnham[2]	Short[3]
Jamesonite	Bluish gray and cream	Light gray, dark brown, dark gray
Meneghinite	Violet gray and creamy white	Light gray, pinkish brown, steel blue
Plagionite	Bluish gray and grayish white	White to dark gray
Semseyite	Pale creamy brown and pale violet	Light gray, bluish gray, brown, dark brown
Weissite	Cream and sky-blue	Pink, bluish gray
Zinkenite	Pale brown and grayish white	White to dark gray

Tarnishing reactions also vary. One hundred ore minerals selected alphabetically among the least rare species showed a total of 111 variations in their tarnishing reactions by comparing the data as given by Short with those of Farnham. I have encountered additional variations in both polarization colors and tarnishing reactions as obtained from authentic species that had been verified by x-ray study.

Anderson's determinative data for meneghinite, with the exception of the microchemical test for copper, also indicates boulangerite, cosalite, galenobismutite, geocronite, plagionite and semseyite. Of this group cosalite contains copper. Normally Cu is not found in galenobismutite but the mineral from Quartzburg, Idaho, was reported by Shannon to contain 1.73 per cent Cu.[4] This is apparently due to impurities. X-ray diffraction studies of meneghinite indicate the absence of copper. The small amounts of copper reported in analyses are, "doubtless due to impurities."[5] Copper in small amounts may substitute for Pb in one variety of geocronite but this has not

[1] March–April, 1946, vol. 41, pp. 105–123.
[2] Determination of the opaque minerals, N. Y., 1931.
[3] Microscopic determination of the ore minerals, Washington, 1940.
[4] Jour. Wash. Acad. Sci., vol. 11, 1921, p. 298.
[5] Palache, Charles, Berman, Harry and Frondel, Clifford: The System of Mineralogy, vol. 1, 7th edition, N. Y., 1944, p. 403.

been established. It is obvious that a microchemical test for Cu cannot be used as a confirmatory test for meneghinite.

The properties as given for guitermanite (= baumhauerite) apply equally well to 11 other ore minerals.

Mention of the above minerals should be sufficient to indicate the necessity of obtaining satisfactory diagnostic data in microscopic identifications. The fact that such diagnostic data can usually be obtained forms the basis of an article recently prepared by the writer.

ERNEST E. FAIRBANKS.

SOUTHERN EXPERIMENT STATION,
BUREAU OF MINES, TUSCALOOSA, ALA.,
May 6, 1946.

REVIEWS*

Features of the Moon—Geology Applied to Selenology. By J. E. SPURR. Part I, The Imbrian Plan Region of the Moon, pp. 112; figs. 23; pls. 4 (2nd printing). Part II, The Features of the Moon, pp. 318; figs. 72; pls. 10 (1st printing). Science Press Printing Co., Lancaster, Pa., 1945. Price: $5.00.

This interesting book by one who is a geologist and not an astronomer deals with the features of the moon as interpreted by a knowledge of geology. Part I, which is a reprinting of an earlier book published in 1944, takes up the features of certain moon craters, selenological phenomena of the Imbrian region, lunar ash distribution, classification of moon depressions, nature of the moon crust, sequences in the Imbrian plain, patterns of Imbrian craters, the Frigoris region, and cycles of crater formation. This part is largely descriptive and clearly tempered by a knowledge of earth volcanoes, but it is a bit hard to follow unless one is well versed in the unfamiliar names of the geographic features of the moon.

Part II has 25 chapters, of which some of the headings relate to: The Imbrian trough and fault system, pre-Imbrian craters, unmelted fault ridges, various grabaters groups and vestiges in remelted regions, remelting and refusion, the Mare Humorum and various other mares, the Frigoris Fault, conditions during lunar historical period, shrinkage and appression, resumé, and summary of moon sequence.

There is portrayed a succession of volcanic eruptions, growth of a siliceous crust, fissuring, domal uplift, collapse graben formation, graben-crater formation, calderas, ash ejections, great trough formation, sinking of mare basins, and isostatic adjustments. The various interpretations are based upon earth geology and the great fault structures, for example, appear to be as clearly depicted as are those in some of the author's own field areas.

The volume is interesting reading for the geologist and should be even more so for the astronomer.

Guidebook to the Geology of Utah, No. 1—Geology and Geography of the Henry Mountain Region. By CHAS. B. HUNT. Pp. 51; figs. 12; folded maps. Utah Geol. Soc., Salt Lake City, 1946. Price, $1.50.

This is the first of a series of guidebooks, to be issued by the Utah Geological Society at the rate of one each year, to a place or region of outstanding interest to geologists. The guidebooks are intended to make familiar outstanding regions that illustrate significant scientific principles in order that visitors can find interesting localities and geological features.

This first guidebook was prepared in cooperation with the U. S. Geological Survey and is really a preliminary issue of text and maps that are being prepared as a comprehensive report by the U. S. Geological Survey.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

This guidebook covers the area made classic by G. K. Gilbert in his outstanding work on the "Geology of the Henry Mountains" published in 1877. It carries descriptions and maps of the most accessible localities and illustrates the author's concept of the form of the intrusions and the origin of the piedmont gravel benches.

There is a description of the general geology of the region as a whole covering stratigraphy, structure, petrography, physical geography, Tertiary history and resources. There then follows detailed structural geology of the following localities: Mt. Ellen stock; Copper Ridge, Bull Creek and Horseshoe laccoliths; Bull Mountain bysmalith; and the physiography of these localities.

The Utah Geological Society is to be commended for their extremely worth while program. If the succeeding volumes keep up to the excellent standard of No. 1, a valuable set of reports will result.

Geology as a Profession. By ANN R. TAYLOR. Pp. 20; illustrated. National Roster of Scientific and Specialized Personnel, Vocational Booklet No. 1, Washington, D. C., 1946. Price, 10 cents.

This booklet describes the profession of geologists, not including geophysics. It gives the subdivisions of the geological profession, working conditions and types of employment, opportunities for women, related fields of employment, beginning jobs, advancement and conditions of employment, postwar outlook in the profession, qualifications and training, along with suggestions as to how to get a start. It is of special value to advisers of young students, and while written primarily from the employment point of view also gives those entering the profession a condensed and business-like summary of what they may expect.

Miss Taylor wrote this pamphlet under the direction of Dr. W. T. Read, Chief of the Research Section of the U. S. Employment Service of the Department of Labor, and was assisted by about twenty other geologists. The booklet may be secured from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., for ten cents.

Rock Tunneling with Steel Supports. By R. V. PROCTOR AND T. L. WHITE, with Introduction to Tunnel Geology by Karl Terzaghi. Pp. 271; figs. 184. Commercial Shearing and Stamping Co., Youngstown, Ohio, 1946. Price, $2.50.

Section I with 5 chapters by the well known authority Karl Terzaghi deals in chapter 1 with the principal types of rocks, their origin and properties; and in chapter 2 with mechanical defects of rocks such as joints, faulting, folding, thrusting and particularly faulting and thrusting in relation to tunneling, with examples and illustrations drawn from several of the well known tunnels of the world. Chapter 3 treats of the chemical defects of rocks under causes, defects due to weathering, hydrothermal action, solution and decomposition. Chapter 4, Load on Tunnel Supports, takes up the influence of rock condition or rock load such as rock pressure, earth pressure, stresses, popping, arches, overbreaks and rock load in stratified rocks, jointed, massive, and crushed rocks with mathematical data. Of particular interest is a part dealing with earth pressure phenomena in decomposed rock and clay with swelling, slipping and load effects. Chapter 5 deals with forecasts of pressure and working conditions in rock tunnels.

Section II deals with the selection and support of various types of ground. Section III covers dimensioning of tunnel supports, and Section IV is a catalog of steel supports.

The book is well illustrated with photos and drawings, and Section I should be of much interest to engineering, structural and mining geologists.

German for the Scientist. By PETER F. WIENER. Pp. 238. Chemical Publishing Co., Brooklyn, N. Y., 1946. Price, $3.50.

This is the type of book needed by scientific students and research workers who desire to obtain in as brief a period as possible a reading knowledge of German scientific literature for reserch, development or engineering work. It has a simple and direct method of approach without too much entangling grammar.

Part 1 gives a brief summary of grammatical and construction difficulties, and the elements of scientific German, with useful hints to avoid these difficulties. Parts 2 and 3 embrace passages from scientific literature, chiefly from physical and chemical works, but of broad scientific value. Part 4 contains the translations of the passages in parts 2 and 3. A 33-page vocabulary is at the end.

Marine Microbiology: A Monograph on Hydrobacteriology. By C. E. ZOBELL. Pp. 240; figs. 12. Chronica Botanica Co., Waltham, Mass., and G. E. Stechert & Co., New York, 1946. Price, $5.00.

This nicely printed volume includes text matter of wider interest than the title might imply. It is not only an outstanding work of great value to biologists, but it has wide interest to geologists interested in paleontology, sedimentation, soils, petroleum and economic geology, particularly the origin and deposition of coals, sulphur compounds, nitrogen, petroleum compounds and phosphates.

It deals with marine environment, collecting, counting, factors influencing distribution, microorganisms of bottom deposits and their activities, transformation of organic matter, the nitrogen and phosphorus cycles, transformation of sulphur compounds, relation of marine bacteria to flora and fauna, economic importance of marine microorganisms, and microbiology of inland waters such as the Black Sea.

This scholarly work is a storehouse of information to all investigators interested in the work of bacteria and particularly the results of such work in the formation of petroleum and non-metallic mineral deposits.

BOOKS RECEIVED.

Mineral Resources of Uganda. By K. A. DAVIES. Pp. 24; map. Uganda Geol. Surv. Entebbe, 1942. Supplements of 1943 and 1944. *Brief description of occurrence and production of various minerals (withheld during war), chiefly gold, tin, tungsten, bismuth and asbestos.*

Mineral Resources of Japan. Compiled by NELSON DICKERMAN. Pp. 118; charts 7; tables. Foreign Minerals Survey, U. S. Bureau of Mines, Vol. 2, No. 5, Oct., 1945 (1946). Washington, D. C. *A careful compilation based upon the information then available regarding Japanese mineral resources, giving names of mines, location, production, imports, exports, consumption, plants, smelters, refineries, ownership of each of the various metals and minerals.*

Mineralogical and Physical Composition of the Sands of Oregon Coast from Coos Bay to Columbia River. By W. H. TWENHOFEL. Pp. 64; figs. 13. Oregon Dept. Geology and Mineral Resources. Bull. 30, Portland, 1946. Price, 35 cents. *Comprehensive study of beach sands; their origin and mineral content; some magnetite, ilmenite and chromite.*

Petrological Studies on Some Basaltic Rocks from East Greenland (with appendix on field position by H. G. Backlund). By T. KROKSTRÖM. Pp. 73; figs. 5; pls. 2. Meddelelser Om Grønland, Bd. 103, Nr. 6. Copenhagen, 1944. *Chemical and petrographic study of basalts.*

World Orientation Atlas—a global desk study unit, student edition. 28 pp. of maps, 12 × 16 in. C. S. Hammond & Co. New York, 1945. Price, $1.00. *A part of the Hammond atlas accompanying Encyclopedia Britannica World Atlas. Maps show world air distances, great circle distances, and setting of Human society.*

Meteorology with Marine Applications. W. L. DONN. Pp. 413; tables 24; profusely illustrated. McGraw-Hill Book Co. New York, 1946. Price, $2.75. *This book is primarily intended to assist young seamen to prepare themselves for marine license examinations, but it is an up-to-date treatise on meteorology, in simple language, with applications to the sea.*

Petroleum Requirements—Postwar. Hearings before a Special Committee Investigating Petroleum Resources. U. S. Senate. Pursuant to S. Res. 36. Pp. 119; charts. October, 1945. U. S. Government Printing Office, Washington, 1946. *Statements of S. P. Coleman, Standard Oil of N. J.; Capt. L. P. Pagett, Navy Dept.; Brig. Gen. H. L. Peckham, War Dept.; A. G. White, Bureau of Mines; R. E. Wilson, Standard Oil of Indiana; Capt. C. P. Franchot, U. S. Navy; and R. M. Weidenhammer, Bur. For. & Dom. Commerce. Statements of production, products, capacities, resources, requirements for present, future forecasts, war requirements and suggested measures for ensuring future military supplies.*

Nickel-Copper Prospect Near Spirit Mountain, Copper River Region, Alaska. J. KINGSTON AND D. J. MILLER. U. S. Geol. Surv. Bull. 943–C. Pp. 49–57; figs. 3. Washington, 1945 (1946). *Non-commercial bodies with bravoite and pentlandite with yellow sulphites in altered basic sill-like intrusives.*

Chromite-bearing Sands of the Southern Part of the Coast of Oregon. A. B. GRIGGS. U. S. Geol. Surv. Bull., 945–E. Pp. 111–150; maps. Washington, 1945. *"Black sand" beach and terrace deposits containing chromite, ilmenite, zircon magnetite and other heavy minerals. Over 3 million tons of sand averaging 3 to 5% Cr_2O_3; war-time concentration up to 40%.*

Mineral Investigations of the Geological Survey in Alaska in 1943 and 1944. J. C. REED. U. S. Geol. Surv. Bull. 947–A. Pp. 1–6. Washington, 1946. *Notations of field work.*

Bibliography of North American Geology, 1942 and 1943. EMMA M. THOM. Pp. 460. U. S. Geol. Surv. Bull. 949. Washington, 1945 (1946). *Another of the well-known invaluable series.*

United States Government Manual—1945, 2nd ed. Pp. 692. Bur. of Budget. Washington, D. C., 1946. *Official handbook dealing with the organization and functions of every agency of the U. S. Government including the Emergency War Agencies.*

Functions and Organization of the Geological Survey of India. J. A. DUNN. Pp. 6. New Delhi, India. *Brief description of organization.*

Minerals of the Montmorillonite Group: Their Origin and Relation to Clays and Soils. C. S. ROSSARD AND S. B. HENDRICKS. Pp. 79; pls. 8; figs. 9. U. S. Geol. Survey Prof. Pap. 205. Washington, 1945 (1946). *Detailed systematic study; determination of limits of variation in composition; underlying causes of base exchange; lattice structures; relation of composition to conditions of formation; alkalic feldspars and micas alter to kaolin minerals and calcic feldspars, ferromagnesian minerals and volcanic glasses to montmorillonite group.*

Quicksilver-Antimony Deposits of Huitzuco, Guerrero, Mexico. J. F. MCALLISTER AND D. H. ORTIZ. U. S. Geol. Surv. Bull. 946–B. Pp. 49–71; maps. Washington, 1945 (1946). *The unique and formerly important La Cruz mine contains replacements of dolomite breccia and rubble filled solution cavities by livingstonite (rare HgSb mineral) and stibnite.*

Scheelite Deposits in the Northern Part of the Sierra de Juarez, Northern Territory, Lower California, Mexico. CARL FRIES, JR., AND E. SCHMITTER. U. S. Geol. Surv. Bull. 946–C. Pp. 72–101; maps. Washington, 1945 (1946). *Tactite replacements of calcareous pendants near quartz-diorite contacts carrying scheelite; war-time importance.*

Tungsten Deposits of the Southern Part of Sonora, Mexico. J. H. WIESE AND S. CARDENAS. U. S. Geol. Surv. Bull. 946–D. Pp. 103–130; maps. Washington, 1945 (1946). *Relatively small contact-metamorphic, pegmatite and quartz vein deposits, of war-time importance only.*

San José Antimony Mines Near Wadley, State of San Luis Potosí, México. D. E. WHITE AND J. GONZÁLES, JR. U. S. Geol. Surv. Bull. 946–E. Pp. 130–153; figs. 22; maps. Washington, 1946. *General geology and descriptions of manto deposits; future rests on successful treatment of low-grade oxide ores.*

Building Blocks from Natural Light-weight Materials of New Mexico. D. M. CLIPPINGER. Pp. 40; pls. 6; figs. 8. Socorro, N. M., 1946. *Deposits, quality, specifications, tests of scoria and pumice for blocks.*

Reports on the Geology and Hydrology of Coastal Area East of Akwapim Range, Gold Coast. N. R. JUNNER AND D. A. BATES. Pp. 23; maps. Geol. Surv. Mem. 7. Accra, Gold Coast, 1945 (1946). Price, 6s. *Geology and hydrology of Archean gneisses and Tertiary deposits; water supplies.*

Physiography and Igneous Geology of Hong Kong and New Territories. M. Y. WILLIAMS, R. W. BROCK, S. J. SCHOFIELD AND T. C. PHEMISTER. Pp. 18. Trans. Royal Soc. Canada, Sec. 4, Vol. 39, 1945 (1946). *Physiography and geology of an area of Laramide granitic intrusives, Paleozoic and Mesozoic sediments and Mesozoic and Tertiary volcanics.*

Explanation of the Geology of Degree Sheet No. 17 (Kahama). D. R. GRANTHAM, B. N. TEMPERLEY AND R. B. MCCONNELL. Pp. 39; figs. 5; maps. Tanganyika, Geol. Div. Bull. 15. Dodoma, 1946. *Physiography, water supply, general geology of Archean volcanics, porphyries, ironstones and sediments and granitic, ultrabasic and dolerite intrusives; economic geology of gold quartz reefs.*

Geological Survey of South Africa, Jubilee Volume. Pp. 234. Vol. 48, 1945. Johannesburg, 1946. Price, 2 guineas. *19 papers relating to the history of the Geological Society, Pleochroic cassiterite, Upper Rand series, chrome, manganese, vanadium, rare elements, asbestos, petrology and tillites.*

Geological Aspects of Prospecting and Areas for Prospecting in the Zinc-Lead Districts of N. W. Illinois. H. B. WILLMAN, R. R. REYNOLDS AND P. HERBERT, JR. Pp. 48; figs. 7; maps. Ill. Geol. Surv. Rep. of Investig. 116. Urbana, 1946. *Stratigraphic position of ore bodies, structure, descriptions, origin, geophysical exploration, and areas for prospecting.*

Scheelite Deposits at Glenorchy, New Zealand. J. J. REED. Pp. 22; figs. 4; pls. 5. Trans. Roy. Soc. New Zeal. Vol. 75, pt. 3. *A petrofabric investigation of structural controls of minor tungsten deposits.*

Silicified Rock in the Ogallala Formation. J. C. FRYE AND ADA SWINEFORD. Pp. 36; pls. 8. Univ. of Kansas Pub., Bull. 64, pt. 2. Laurence, Kans., 1946. *Occurrence, investigation and origin of chert and quartzite and possible uses.*

SOCIETY OF ECONOMIC GEOLOGISTS

The Nominating Committee of the Society of Economic Geologists consisting of Dr. Henry R. Aldrich and Dr. A. I. Levorsen under the chairmanship of Dr. M. M. Leighton have submitted the following nominations for officers in the Society during the coming year:

For President, 1948: Thomas M. Broderick
For Vice President, 1948: Sidney Paige
For Councilors, term ending 1949: Ernest F. Bean
Gilbert H. Cady
J. E. Hawley

For Regional Vice Presidents, 1947:

For Europe: David Williams
Asia: P. K. Ghosh
Africa: Hendrik Jan Schuiling
North America: Ezequiel Ordõnez
South America: Jorge A. Broggi
Australia: R. Lockhart Jack

This nomination does not constitute either a ballot or election. The members are invited to submit in writing to the Secretary the names of other candidates whom they wish to have considered.

R. N. FRANTIŠEK ULRICH

1899–1941

Heavy losses were suffered by Czech science during the German occupation. In the last issue of "Naše věda" ("Our Science") there is a list of 74 Czech scientists who were executed or lost their lives in concentration camps. Among them was Frantisek Ulrich, Professor of Experimental Mineralogy at the Karlova University, Prague, and a member of the Society of Economic Geologists. Professor Ulrich was killed at the age of 42 when arrested by the Gestapo in his own apartment, October 21, 1941.

In Professor Ulrich Czech mineralogy lost an outstanding man of high intelligence, a teacher devoted to his science, a broadly trained investigator, and an excellent organizer. He studied at the University of Prague, 1918–1922; in the years 1924 and 1925 a Rockefeller Fund Scholarship enabled him to complete his studies at the University of Oslo in the laboratories of Professor V. M. Goldschmidt. There he specialized in structural crystallography and roentgenometric and metallographic methods. After his return he lectured in mineralogy at the well-known School of Mines at Příbram. In 1934 he was appointed to the post at Karlova University.

Ulrich's widely ranging activity extended from mineralogy and crystallography into many related fields, especially petrography, applied geology and radiology. I

mention only some of his most important papers:

Contribution a l'étude des phosphates de fer et d'alumine: Bullet. de l'Acad. de Science de Boheme, 1922.

Note sur la composition mineralogique des minerais de cuivre a Verneřovice: Bullet. de l'Acad. de Scien. Boh., 1924.

Notiz über die Kristallstruktur der Korund-Hämatit Gruppe: Norsk Geol. Tidskript VIII.

Cristallographie de la vivianite de Rona veeche: Bullet. intern. de l'Acad. de Scien. Boh., 1924.

A good part of Professor Ulrich's activity was devoted to studies of the deposits of useful rocks and minerals, especially the ores of copper and manganese and deposits of magnesite, and in general to the genesis of economic minerals in Slovakia. Of these papers the most important are:

Les gites giobertite en Tchécoslovaquie et l'etat actuel de leur exploitation: II Congres de Chimie Industrielle, Prague, 1932.

Les gites de minerais de manganese dans les Carpathes du nordouest en Tchécoslovaquie et leur genése: Prague, 1936.

Ulrich's work was interrupted by the occupation and on November 17, 1939, with many other scientists, he was expelled from his institute. Afterward and until his death he worked at the Museum of Natural History at Hradec Kralove in Eastern Bohemia.

We remember Professor Ulrich in these days, when we are about to rebuild our scientific institutions on the ruins left by the enemy. We sorely miss his helping hand.

QUIDO ZARUBA

May 24, 1946

SCIENTIFIC NOTES AND NEWS

FRANK F. GROUT has resigned as Director of the Minnesota Geological Survey to devote full time to teaching and completion of field and research problems. The Regents of the University of Minnesota have appointed Professor George M. Schwartz to the Directorship.

WALTER F. POND, formerly State Geologist of Tennessee for 18 years, has accepted the position of geologist for the Magnet Cove Barium Corporation at Malvern, Arkansas. In addition to handling the company's geologic problems in connection with Arkansas barite deposits, Mr. Pond will investigate and do geologic work on other mineral holdings of the company in various parts of the United States. His headquarters will be at Malvern, Arkansas.

MAHLON MILLER has just made a trip through the tin mining districts of the peninsular section south of Bangkok in Siam. Harold Kirkemo is working with him there.

DAVID GALLAGHER is in Seoul, Korea, where he is in charge of the Korean portion of the investigation of the mineral resources and mineral deposits of the Japanese Empire. He is also Director of the Korean Geological Survey and Institute of Mining Technology. M. Klepper, Dewey Sample, William Overstreet street and Thomas O'Byrne are working with him.

JOHN J. COLLINS is with the Mining and Geology Division of the Natural Resources Section in Tokyo, and is now examining and writing reports on some of the larger copper mines of Japan.

ALI A. HASSON, geologist and engineer of mines, died June 7 at the age of eighty-six.

T. B. WILLIAMS has been appointed Commissioner of Petroleum and Natural Gas for British Columbia. This is a new Commission recently set up in the B. C. Department of Lands.

W. E. WRATHER, Director of the U. S. Geological Survey has gone on a trip to Alaska in company with Secretary Krug.

PER GEIJER, Associate Editor of this journal, and of the Swedish Geological Survey, writes from Stockholm that he plans to make a brief visit in the United States in October to attend by invitation the meetings of the National Academy and the American Philosophical Society.

ROY FULL, formerly with the U. S. Geological Survey is now associated with P. Shenon in Spokane, Wash.

EDGAR BOWLES has been appointed Assistant Professor of Geology at Rutgers University, New Brunswick, N. J., upon his return from the Sinai Desert, Egypt where he was engaged in oil geology.

W. H. NEWHOUSE has been appointed Professor of Economic Geology at the University of Chicago. He will assume teaching duties there in October.

R. M. DREYER has been made Associate Professor of Geology at the University of Kansas.

W. F. JENKS has joined the Department of Geology at the University of Rochester upon his return from Arequipa, Peru.

CARL TOLMAN, recently with the F. E. A. in Washington, and now chairman of the Department of Geology at Washington University, has been appointed acting dean of the School of Graduate Studies.

WILLIAM B. MATHER, of the Missouri Geological Survey at Rolla, has now joined the staff of the Midwest Research Institute to engage in economic geology and petrography.

J. W. CLARK has left the Union Mines Corp. to become geologist with Spectrographic Services and Supplies, Saratoga Springs, N. Y.

GEORGE M. SCHWARTZ, director of the Minnesota Geological Survey and a professor of geology at the University of Minnesota, has been elected a "corresponding member" of the Geological Society of Belgium in recognition of his contributions to the geological science.

E. W. ELLSWORTH has returned from the Natural Resources Section of General MacArthur's staff to resume his consulting practice at Centralia, Ill.

E. T. HECK, of the New York State Geological Survey has been appointed chief geologist of the Quaker Oil Co.

H. B. MAUFE, formerly Director of the Southern Rhodesian Geological Survey died in London on May 6.

H. DEWITT SMITH of Newmont Corporation left in August for a trip to the O'Okiep Mine in Africa.

THOROLD VOGT of the Norges Tekniske Hogskole, Trondheim University, Norway states that Dr. V. M. Goldschmidt of the University of Oslo although recently arrested during the German occupation was freed each time upon the urgency of his colleagues and of the University and its President, Dr. Solberg. The last time he was saved from being sent to Germany by the direct intervention with a German General Marthinsen just as he was going up the gangplank. Later he was smuggled out of Norway to Sweden and from there to Great Britain. Dr. Carl Bugge, Director of the Geological Survey of Norway, managed to save the collections, archives and libraries at Oslow. Although the offices were badly bombed he, himself, got safely through the War. Professor Vogt also escaped with his life, although he took part in quite a bit of the underground work.

G. G. SUFFEL who has been on the geological staff of Noranda Mines, Quebec, and the Waite-Amulet mine since 1929 has left to join the geological staff of the University of Western Ontario, London, Ontario, where his teaching will be principally in Economic Geology.

The Second Pan American Congress of Mining Engineering and Geology will be held in Rio de Janeiro, Brazil, during this coming October. Meetings will be held in Rio and the following excursions are planned: (1), Charcoal iron production and iron ore exploitation, Oct. 6–13, visiting Victoria iron plant; Governador Valadares, Minas Gerais, mica mines; President Vargas, M. G., iron properties; Monlevade; Morro Grande, iron properties; Belo Horizonte, M. G., entertainments and industries; Morro Vehlo gold mines; Ouro Preto, Esperanca plant, aluminum plant, conferences. (2), Gold, Manganese, Quartz and Minas Gerais pre-Cam-

brian Formations, Oct. 5–13 visiting Conselheiro Lafaiete, M. G., Morro da Minas manganese deposit and the Casa da Pedra iron ore mine; Belo Horizonte, M. G.; Diamantina, M. G., city, diamond mines, and Joquitinhonha river; Belo Horizonte, industries and entertainment; Morro Velho gold mines; Ouro Preto, M. G., Esperanto and aluminum plant, entertainment. (3), Coals of South Brazil, Oct. 6–13, visiting Santa Catarina coal plants and mines, and Urucanga, Criciuma koal mines; Porto Alegre, Rio Grandè do Sul and nearby Sao Jeronimo and Butia coal mines; Volta Redonda steel mill. (4), Bauxite, Zircon and Metallurgical industries, Oct. 6–13, visiting Araxia, M. G.; thermal springs; Pocos de Caldas, M. G., bauxite and zircon deposits; Sao Paulo, tungsten mine and Rodovalho aluminum plant; Mogi das Cruzes iron plants; Volta Redonda steel mill. (5), Geology of South Brazils Gondwanda regions, Oct. 6–13, visiting Florianopolis, Imbituba, Cabecudas, Capivari, Sta. Cat., coal, geology, and Whites geologic column; Lages, geology and nephelenite, conferences; Rio do Sul; Curitiba, Parana.